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Journal

of

THE ROYAL AERONAUTICAL SOCIETY

JULY 1958

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All communications for publication in, and advertisements for, the JOURNAL *should be addressed to the Editor,* JOAN BRADBROOKE, *A.R.Ae.S.; all communications on general matters affecting the Society should be addressed to the Secretary,* A. M. BALLANTYNE, *T.D., B.Sc., Ph.D., Hon.F.C.A.I., A.F.I.A.S., F.R.Ae.S.*

None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless otherwise stated.

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Secretary's News Letter

July 1958

THE AIRCRAFT of the Nash Collection, now owned by the Society, are in need of maintenance. They are housed at Hendon, and access to them has been granted to the Society.

With the aid of Members of the Society I should like to form a Maintenance Working Group to make regular visits to Hendon so that the aircraft are kept in a state of good repair. The aircraft at Hendon are

Sopwith Camel
Bleriot Type XXVII
Caudron G.III
Avro 504K
S.E.5A
Maurice Farman
Fokker D.VII

I should like all those interested in maintaining the old aircraft to write to me stating any experience they may have had.

I hope that many will come forward to renew former associations; equally do I hope that not a few of a younger generation will be sufficiently interested to make contact more intimately with the Nash Collection, which typifies the older thoughts in aircraft design.

A. M. Ballantyne

Secretary.

NOTICES

August Bank Holiday

The Library and Offices of the Society will be closed from Friday afternoon 1st August until 9 a.m. on Tuesday 5th August.

Associate Fellowship Examinations—December 1958

The closing date for Candidates in the United Kingdom for December 1958 Examinations is 31st August. Entry forms may be obtained from the Secretary. The closing date for entries outside the United Kingdom was 30th June.

History of Aviation—Slides

Flight Lieutenant J. Glover (*Associate Fellow*) of 33 Southampton Road, Fareham, Hants, has a lecture series of 3¼ in. by 3¼ in. slides illustrating the history of aviation, from hot air balloons to the Ambassador. There are 111 slides and any member interested in buying the collection should contact Flight Lieutenant Glover.

Acknowledgment

The Council wishes to thank Flight Lieutenant J. Glover, *Associate Fellow,* for presenting over fifty old books, manuals, pamphlets and back numbers of the Journal to the Library.

Soviet Abstracts—Mechanics

The Ministry of Supply is now sending the monthly "Soviet Abstracts—Mechanics" to the Library. These are translations of the Russian items in Referativnyi Zhurnal, the abstract service of the Soviet Academy of Sciences.

Birthday Honours List

C.B.
M. B. Morgan (*Fellow*)
Group Captain S. W. Lane (*Associate Fellow*)
C.B.E.
Dr. E. S. Moult (*Fellow*)
O.B.E.
L. Haworth (*Associate Fellow*)
M.B.E.
Squadron Leader J. W. Whitelegg (*Associate Fellow*)
Queen's Commendation for Valuable Service in the Air
Squadron Leader J. S. Booth (*Associate*) (Deceased)
G. L. Howitt (*Associate*)
M.V.O.
J. R. Finnimore (*Associate Fellow*)

International Congress—Madrid

Members of the Society have already received a notice about the First International Congress of the Aeronautical Sciences which is to be held in Madrid from 8th to 13th September 1958 under the Chairmanship of Dr. Theodore von Kármán. Those wishing to attend the Congress who have not yet applied to the Secretary of the Society for application forms are advised to do so as soon as possible as, with twenty countries participating in the Congress, accommodation in Madrid may be limited.

The Congress will be held in the Instituto Nacional de Prevision, Alfonso XI, Madrid, and more than 40 papers have been selected for presentation. The programme of papers to be given is on p. XX of these Notices.

Elections

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Edward Sydney Coombes
Fisher Bruce Crockett
Peter John Daglish
Gordon Davies (*from Graduate*)
Bimal Chandra Dutta (*from Companion*)
Frederick Henry East
William Godfrey Fairhead (*from Graduate*)
Gordon Stanley Gee (*from Associate*)
Jack Womersley Headley (*from Graduate*)
John William Higgins (*from Associate*)
Gordon James Hunt (*from Graduate*)
John Douglas Jones (*from Graduate*)
John Stuart King
Ralph Victor Lamarra
Edgar Duncan Goodenough Lewin
William Robert McLean (*from Graduate*)
William Francis Meichan (*from Graduate*)
Norman James Munro (*from Graduate*)
John Edward Nethaway (*from Graduate*)
Norman Llewellyn Prewett
Denys Randolph (*from Graduate*)
Robin Salmon (*from Graduate*)
Alan Allnut Saw
Allan Francis Stewart
Archibald Douglas Weir
Donald Royston Willmer (*from Graduate*)

Associates

Paul Anthony Arondel
Mirza Saleem Anwar Beg
Edward John Carden
Kenneth Dewar
Ralph Harold Hayward
John Sproul Hood
John Bertie Karamath
William Henry Lowe
Douglas Ernest Matthews
Royston Bruce Morrill
Desmond Henry Pells
Vivian Ronald Smith
Eric Staddon
Bernard Thacker
Philip William Wilkinson

Graduates

Richard Derek Gommo
Geoffrey Acton Hamer
James William John Hawkins
Alan John Lyne (*from Student*)
Keith Patrick McMahon
Brian Rothnie (*from Student*)
Brian Joseph Summers
Alan Thirkettle
John Edward Wingate (*from Student*)

Students

Ian Robert Orchar Brand
John William Britton
Robin Timothy Burns
David John Coombs
Frederick Brian Ellis
Saggere Narasimha Murthy
Paul Michael Francis Nagle
William John Rix
Ian James Rouet
John Graham Tait
Colin Foreman
Cherusseri Radhakrishna Menon
Robert Stephen Whitfield
K. Mohamed Ziauddin

Companions

James Cuming
Norman Denis Holdsworth

News of Members

A. Beedle (*Associate*), formerly with Saunders-Roe Ltd., is now an Aerodynamicist with Westland Aircraft Ltd.

N. K. Benson (*Graduate*), formerly with Handley Page Ltd., is now with CIBA (A.R.L.) Ltd. (formerly Aero Research Ltd.), Duxford, as Assistant Head of the Structures Laboratory.

R. F. Beresford (*Associate Fellow*), formerly a Lecturer at Northampton Polytechnic, has been appointed Senior Lecturer in the Mechanical Engineering Department of the Municipal College, Bournemouth.

I. H. Blick (*Associate Fellow*) has been transferred from the de Havilland Aircraft Company Ltd. at Christchurch to the Technical Sales Organisation Department of the de Havilland Engine Company Ltd., Leavesden.

D. A. Brown (*Associate Fellow*), formerly of Bristol Aircraft Ltd., is now a Stress Engineer with Avro Aircraft Ltd., Ontario, Canada.

M. A. Catton (*Associate*) has been promoted to Inspector-in-Charge at Handley Page Ltd., Reading.

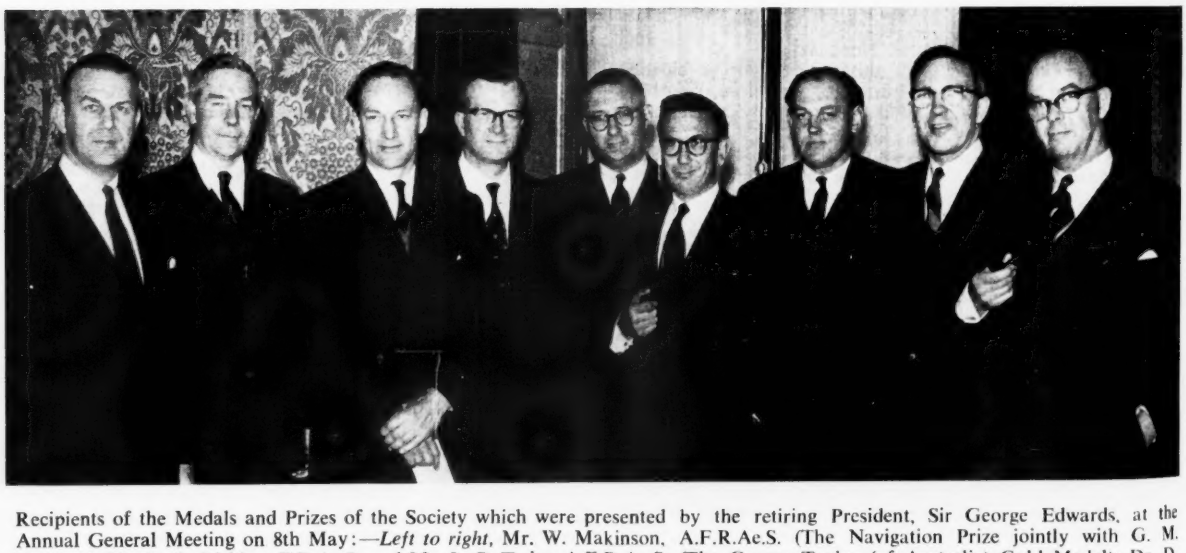
A. F. Constantine (*Associate Fellow*), formerly of Bristol Aircraft Ltd., is now with the British Standards Institution as a Technical Officer.

D. Cressey (*Associate*), formerly Technical Liaison Officer with Bristol Aero Engines Ltd., is now Quality and Investigation Engineer with Bristol Aero Engines (Western) Ltd., Vancouver, Canada.

Squadron Leader R. Dimberline (*Associate Fellow*) is now Project Officer, Guided Weapon Squadron, Central Servicing Development Establishment, Royal Air Force.

J. S. Gibbs (*Associate*), formerly Inspector-in-Charge, Vickers-Armstrongs (Aircraft) Ltd., Weybridge, now holds the same position with the de Havilland Aircraft Company Ltd., Hatfield.

A. G. R. Gilbert (*Associate Fellow*), formerly Section Leader of the Drawing Office at the de Havilland Engine Company, is now Assistant Design Engineer.



Recipients of the Medals and Prizes of the Society which were presented by the retiring President, Sir George Edwards, at the Annual General Meeting on 8th May:—*Left to right*, Mr. W. Makinson, A.F.R.Ae.S. (The Navigation Prize jointly with G. M. Hellings); Mr. R. L. Lickley, F.R.Ae.S. and Mr. L. P. Twiss, A.F.R.Ae.S. (The George Taylor (of Australia) Gold Medal); Dr. D. Kuchemann, F.R.Ae.S. (The Edward Busk Memorial Prize); Mr. G. M. Hellings, A.F.R.Ae.S. (The Navigation Prize jointly with W. Makinson); Mr. M. B. Morgan, C.B., F.R.Ae.S. (The Branch Prize); Mr. L. F. Nicholson, F.R.Ae.S. (The Simms Gold Medal); Dr. R. R. Jamison, F.R.Ae.S. (The Herbert Ackroyd Stuart Memorial Prize) and Professor A. R. Collar, F.R.Ae.S. (The Orville Wright Prize). Full details of the Medals and Prizes of the Society, presented at the Annual General Meeting were published on page XXV of the June 1958 *Journal*.

Sir George Edwards, retiring President investing Sir Arnold Hall, the incoming President, with the Presidential badge of office at the end of the Annual General Meeting on 8th May.

Sir Arnold Hall presenting the scroll of Honorary Fellowship to Sir Richard Southwell at the Wilbur Wright Memorial Lecture on 15th May.

(1) (2) (3) (4) (5)

Medals and awards presented at the Wilbur Wright Memorial Lecture:—(1) Mr. W. E. Nixon, who was presented with the scroll of Honorary Companionship; (2) Sir Sydney Camm, F.R.Ae.S., who received the Society's Gold Medal; (3) Dr. P. B. Walker, F.R.Ae.S., receiving the Society's Silver Medal; (4) Dr. D. Williams, F.R.Ae.S., receiving the Society's Bronze Medal; and (5) Mr. S. D. Davies receiving the British Gold Medal.

Right: (6) Mr. W. F. Saxton and (7) Mr. W. H. Lindsey, F.R.Ae.S., who received the British Silver Medal; (8) Mr. Walter Tye, F.R.Ae.S., receiving the Wakefield Gold Medal and (9) Mrs. Anne Burns receiving the R. P. Alston medal. Full details of the Medals presented at the Wilbur Wright Memorial Lecture were published on page XXV of the June *Journal*.

(6) (7) (8) (9)

FIRST INTERNATIONAL CONGRESS OF THE AERONAUTICAL SCIENCES—MADRID, 8-13TH SEPTEMBER 1958

The following 45 papers have been selected for presentation at the First International Congress of the Aeronautical Sciences:—

Monday 8th September—*Opening Session*

Daniel and Florence Guggenheim International Memorial Lecture — Th. von Kármán

Juan de la Cierva Lecture — Ing. Pedro Blanco

Tuesday 9th September—*General Session*

Aerodynamic Design for Supersonic Speeds — Robert T. Jones (U.S.)

Telecommand and Navigation — William H. Stephens (U.K.)

Propulsion Supersonique — M. P. Roy (France)

Special Session—Hypersonic Flow

Newtonian Flow Theory in Hypersonic Aerodynamics — W. D. Hayes (U.S.)

Dynamics of a Dissociating Gas — M. J. Lighthill (U.K.)

Experimental Investigation of Hypervelocity Flight — J. Lukasiewicz (U.S.)

Special Session—Structures and Aeroelasticity

Design Loads in View of Non-Linearity — A. van der Neut (Holland)

Paper by Luigi Broglio (Italy)

Représentation d'un système thermoélastique vibrant sans et avec fluage dans la direction de la vibration — Robert Mazet (France)

Aerodynamic Derivatives for Oscillating Three-Dimensional Wings in Transonic Flow — Marten T. Landahl (Sweden)

Wednesday 10th September—*Special Session—Heat Transfer and Heat Barrier*

Mass Transfer Cooling, A Means to Protect High Speed Aircraft — E. R. G. Eckert (U.S.)

The Heat Barrier and Its Influence on Hypersonic Aerodynamics — R. J. Monaghan (U.K.)

Echanges de chaleur dans les écoulements présentant des décollements — R. Siestrunck and Jean-Joseph Bernard (France)

Paper by E. Schmidt (Germany)

Non-Adiabatic Flow in a Rotating Duct — J. M. de Sendagorta (Spain)

Special Session—Jet Engines and Noise

Progress in Jet-Engine Noise Reduction — F. B. Greatrex (U.K.)

Noise Research in Canada: Physical and Bio-Acoustic — K. K. Neely, H. S. Ribner and B. Etkin (Canada)

Noise in Air Transport — William Littlewood (U.S.)

Quelques études sur l'action produite par les jets de réacteurs sur les structures — H. J. L. Le Boiteux (France)

Special Session—Navigation and Guidance

Some Considerations of Safety in Instrument Flight Control — A. M. A. Majendie (U.K.)

Uber dynamisch bedingte Auswanderungserscheinungen an Kreiselgeräten — Kurt Magnus (Germany)

Principles of Inertial Guidance — C. S. Draper, W. Wrigley and R. B. Woodbury (U.S.)

Special Session—Boundary Layer Control

Einige neuere Ergebnisse über Grenzschichtbeeinflussung — H. Schlichting (Germany)

Fundamental Design Problems of Aircraft with Boundary Layer Control for Maintaining Laminar Flow — G. V. Lachmann (U.K.)

Contribution théorique et experimentale a l'etude du contrôle de la couche limite par soufflage — P. Carriere, P. Poisson-Quinton and E. A. Eichelbrenner (France)

The Use of Boundary Layer Control to Establish Free Stream-line Flows — D. G. Hurley (Australia)

Thursday 11th September—*General Session*

Aeroelastic Problems on Aircraft Construction — G. H. Küssner (Germany)

A Review of Some Recent Developments in Hypersonic Flow — Antonio Ferri (U.S.)

Etude de l'aile annulaire par analogie electrique — Prof. Lucien C. Malavard (France)

Friday 12th September—*Special Session—VTOL-STOL*

Research on VTOL and STOL Aeroplanes in the United States — J. P. Campbell (U.S.)

Safety and Reliability Aspects of VTOL — D. Keith-Lucas (U.K.)

La Mécanique de Vol du Propulseur Volant a Décollage et Atterrissage vertical — Gerhard Eggers and Günther Ernst (France)

Special Session—Heat Resistant Materials

Materials and Structures for Finite Lifetime — N. J. Hoff (U.S.)

Problems in Heat Resistant Materials for High Speed Flight and Propulsion — Pol Duwez (U.S.)

Paper by D. A. Oliver (U.K.)

Special Session—Human Engineering

Prospects and Limitations of Human Flight Beyond the Atmosphere — D. G. Simons (U.S.)

Disorientation in Flight — G. Melvill Jones (U.K.)

Les limites psycho-physiologiques du piloté humain et la sécurité du vol — E. Evrard (Belgium)

Special Session—Telecommand and Telemetering

Telemetry and Pilotless Aircraft Control Applications in Australia — R. A. Leslie and P. O. Gillard (Australia)

Transmission of Data by Radio from the U.S. Satellites — J. T. Mengel (U.S.)

Saturday 13th September—*General Session*

Propulsion Methods in Astronautics — W. Moeckel (U.S.)

Physical Basis of Magneto-hydrodynamics — W. B. Thompson (U.K.)

A Comparison of Various Approaches to an Electric Propulsion System — V. H. Blackman (U.S.)

NEWS OF MEMBERS—*Continued*

G. P. HEBDEN (*Associate Fellow*), formerly Chief Project Engineer, Normalair Ltd., is now Development Engineer at Wilmot Breedon Research Laboratories, Warwickshire.

P. V. HOARE (*Fellow*) has been appointed Consultant to Tiltman Langley Ltd. by arrangement with Westland Aircraft Ltd.

F. C. KIRKPATRICK (*Associate*), formerly with Short Brothers and Harland, Belfast, has joined Folland Aircraft Ltd. as Education Officer.

W. L. LAX (*Associate Fellow*), formerly at the Royal Aircraft Establishment, is now in charge of the Drawing Office of the Special Products Division of the J. Langham Thompson Group, Stanmore.

N. L. LUPTON (*Associate Fellow*), formerly with the Sperry Gyroscope Company Ltd., has been appointed Commercial Manager of Microcell Ltd.

T. W. MANN (*Associate*), formerly with Saunders-Roe Ltd., is now Senior Engineer, Weapons Division, A. V. Roe and Co. Ltd., Stockport.

D. P. MANKES (*Student*) is now a Technical Engineer in the Project Group of Bristol Aircraft Ltd.

Commander B. B. MUNGO (*Associate Fellow*), formerly of the Directorate of Naval Aircraft Research and Development, Ministry of Supply, has been posted to the British Joint Services Mission in Washington.

Wing Commander R. H. STOCKEN (*Fellow*) was inadvertently described as *Associate Fellow* in the announcement about Airco in the June Journal. He has been a *Fellow* for a number of years.

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MERVYN O'GORMAN, *Honorary Fellow*
1871 - 1958

MERVYN O'GORMAN was born on 19th December 1871, and died on 16th March 1958. He was educated at Downside School and University College, Dublin, where he took degrees in classics and science. He became well known as a consulting engineer. In 1909 he became the Superintendent of the Balloon Factory at Farnborough, which was to change its name to the Royal Aircraft Factory and later, to the Royal Aircraft Establishment. If any man ever can be said to be responsible for laying the early foundations so well and so truly as they were laid of the R.A.E., that man was Mervyn O'Gorman.

It was his appointment which proved to be the beginning of aeronautical scientific research in this country. He never lost his urgent belief that such research was the key to aeronautical supremacy both in military and civil fields, and throughout his long life he fiercely and eloquently resented any cheese-paring economies where research was concerned. He became a member of the Advisory Committee for Aeronautics in 1909.

Joining the Society in 1910 he was elected a member of Council the following year. He served on the Council for many years, and was its Chairman in 1921-22. He was elected an Honorary Fellow in 1950.

Mervyn O'Gorman was one of the Committee appointed in 1911 to put forward a new organisation for the Society, which had been run for too long by a self-elected Council. In 1914 he was a member of the Technical Terms Committee of the Society which published in the October 1914 JOURNAL the first glossary of aeronautical terms and their meanings. In 1923 he was a Vice-Chairman of and Society representative on the International Air Congress held in London.

He was a great Committee man, not only in the Society, but in other aeronautical bodies, automobile organisations, government departments and international bodies. He was one of the earliest of motoring pioneers, and it is worthwhile recording that in 1912, when charged with reckless driving and exceeding the speed limit, he admitted having driven for thirteen years.

When he was on the defensive his eloquence and wit were of the highest Irish quality. He would have been a great companion with whom to be going down Sackville Street!

Two policemen in plain clothes had tried to stop him as he drove by, and he declared with considerable persuasiveness that he had believed them to be motor bandits, and drove straight at them to prevent them attacking him! One of the technical aeronautical journals headed the account of the case "The Superintendent of the Royal Army Aircraft Factory fined for demoniacal driving!" Nevertheless, the charge was dismissed and he was fined for exceeding the speed limit He had done so, handsomely, by passing the police at 27½ miles an hour! He never lost his enthusiasm for motoring affairs!

Colonel Mervyn O'Gorman, C.B., D.Sc., M.Inst.C.E., M.I.Mech.E., M.I.E.E., F.R.Ae.S. A photograph taken in Vienna in May 1936. The stripes on the tie were Colonel O'Gorman's own handiwork.

The Annual Technical Reports of the Advisory Committee for Aeronautics from 1910 to 1916 reveal the research activities of the new Superintendent, for 14 research papers bear his name.

O'G (his affectionate nickname) had the rare faculty of sensing the potentialities of men he chose, and of inspiring them with his own enthusiasm and energy, an energy which sometimes appeared to grow greater with the years.

I remember in November 1952 talking to him at Imperial College while many friends were gathering together to listen to Roderic and G. T. R. Hill recall

their gliding experiences of 40 years before. Among those who were there were some he had known during those fruitful years at Farnborough, Alec Ogilvie, Melvill Jones, Sempill and others. The world rolled back for him, and his energy that day, his enthusiasm, were those of 1912, when he was in his fortieth year—the same energy still, although he was then turned 80.

Much research was initiated at his suggestion. In the 1913-14 Report, for example, there is a paper by Nayler, Stedman and Stern, "Experiments on an aerofoil having a hinged rear portion," which begins "The following experiments . . . were made at the request of Mr. O'Gorman." I believe these must have been the first experiments on flaps.

O'G had a habit of saying fearlessly what he thought. Few of those who listened in November 1923 to Major Mayo's lecture on "The Development of High Speed Aircraft" will forget O'Gorman's sarcastic attack on the Air Ministry.

"As our lecturer had intimated, all the 'world's records' for speed and performance had settled firmly into the grip of those nations whose technical control was not in the hands of the British Air Ministry."

He poured scorn on the appointment of those without aeronautical knowledge, to be administrators of aeronautical research.

"In so fundamentally scientific and technical a science as the air no such erroneous creed should be capable of acceptance, but so long as it is accepted there is no career for skilled scientists and therefore no queue of good and capable technical persons for the posts they alone can fill."

Mervyn O'Gorman was the Chairman of the Council deputation to the Secretary of State for Air in 1922, which urged the importance of Research in Aeronautics. He had with him Leonard Bairstow, Melvill Jones, Alec Ogilvie and Sir Mackenzie Chalmers. It took three years for the importance of what the Council had suggested to be accepted, for it was not until June 1925 that H. E. Wimperis was appointed as Director of Scientific Research, the outcome of O'G's persistent eloquence.

"The rock on which the whole edifice must be founded is the scientific man," he declared, "and he is nothing at all at the Air Ministry. We have disregarded research completely and that is what is the matter with British aeronautics. . . . The technical side has not been given the position and authority to which it is entitled. . . ."

O'G had a way of putting arguments which was all his own. Ten years before Mayo's lecture, in November 1913, Roger Wallace had lectured to the Society on "The Right to Fly." A suggestion had been put forward that the air space should be free without restriction, and that over it no dominion, sovereign or otherwise, could be imposed. O'G demolished the idea in a typical way.

"When Remus jumped over the wall of Romulus, his passage taking place through the air, it is not reported that Romulus objected because his wall was kicked or damaged. He considered the passage infringed his rights. When aircraft fly over a cover and disturb the birds or fly over crowded places and disturb the Aero Club, we find automatically the words 'the air space is free to all without restriction of any kind' is intolerable to all. That is to say there must be some height limit—and it seems likely that the height limit is the crux of the situation."

O'G gave the Wilbur Wright Memorial Lecture in 1917, under the title "Looking ahead." It was an excellent survey and comment for the time, and one might recall his words, for they could have been written today.

"Aeronautical engineers have lived many years on a diet of hope, exercising their imagination and stimulating others to look ahead; hence they can realise with exceptional clarity how foresight may become dormant in busy men, and so be led to ask themselves 'Now that we are busy, are we as wide awake as we were?'"

O'G was indeed very wide awake, too much so for most of those who did not know how to make use of his great talents. Unfortunately some of "those" had the power to prevent him from receiving the honour and recognition which were, without question, his due. And some of the failure to do him honour must be firmly laid on those who, in the aircraft industry, in Parliament and the Press, in those pioneer years of the R.A.E., distorted the truth about the man who was never afraid to tell it.

Mervyn O'Gorman was a great artist, a great lover of his country, a great gentleman, and a great friend. Those who knew him well, loved him well, and he will remain with them all their lives.

J. LAURENCE PRITCHARD, *Honorary Fellow.*

From Major F. M. Green, O.B.E., M.Inst.C.E., Fellow

WHATEVER the qualities are that make a striking personality, Colonel Mervyn O'Gorman certainly had them. Whether it was his Irish eloquence, his enthusiasm or his undoubted charm, I cannot say, but he made an immediate impression on all who met him.

I had already a slight acquaintance with him when, in 1909, he came to a lunch party at the Daimler works in Coventry where I was employed. He asked me if I knew anyone suitable for the post of "Engineer Design" at what was then called the Balloon Factory. I offered myself and was accepted, and for the next six-and-a-half-years I knew "O'G," as his friends called him, very well. He was a wonderful man to work for because far from the frustration a young man experiences in ordinary jobs, it was rather the other way about. In fact his enthusiasm often led him to ideas that seemed too much in the future.

Looking back over the years, I have lived to see most of his dreams come true. I was lucky enough to lunch with him a few months ago on his 86th birthday, and I felt sad that circumstances had prevented him from taking a more active part than he did in the job he loved so much and did so well.

I doubt if there is any idea among present day aircraft engineers of the romance and difficulties in

those early days of flying nearly 50 years ago. O'G was appointed superintendent of a very small unit run by a reluctant War Office. Money was given grudgingly, because the military mind had no belief whatever in flying. Experiments on aeroplanes by the R.E.s in former years in conjunction with Colonel Cody had not been encouraging enough and we were told to confine our work to Airships. It was ironical that in a competition for military aircraft two or three years later, it was the Cody aeroplane that gained first prize.

So we settled down to make small airships and O'G put his enthusiasm into lighter-than-air craft. At the same time he was a firm believer in the aeroplane but could not get permission to build one.

In 1911, I heard that an old friend of mine, a young man called Geoffrey de Havilland, had designed and built both a biplane and an engine for it. Furthermore, he had taught himself to fly on it. I told O'G about it and he somehow persuaded the War Office to buy the aeroplane and engage de Havilland as pilot. There was still no permission to make a new aircraft, but O'G, with his usual ingenuity, got over the difficulty by "reconstructing" the original machine. This, of course, was mere camouflage, but it worked well enough. We made several reconstructions and the result was that the War Office came to recognise the aeroplane as a war machine.

Before the First World War, the first stable and controllable aircraft was made; the first wireless gear was designed and tested in the air; for the first time in England a machine gun had been fired from an aeroplane and the fastest machine in the world (130 m.p.h.) had been flown with success.

These early aircraft had mostly French engines; no British engine maker took aircraft seriously. True there was the Green engine (which had nothing to do with the writer) but this had no real backing. This situation did not satisfy O'G and he got permission to make a more powerful engine on the lines of the 8-cylinder air-cooled Renault. His vision was soon to be justified, for when the war started, there were available drawings and specifications of a workable aircraft and engine. The chief motor manufacturers were called in and were able to start manufacture without delay.

When the motor trade began to realise that we were in for a long war, some, at least, of our engine designers took an active interest in designs of their own. I remember Sir Henry Royce being asked to design an engine. He sent in a drawing of a 12-cylinder air-cooled engine. O'G explained that such an engine already existed and persuaded him to make it water-cooled, the result was the Rolls-Royce Eagle which played a big part in the later stages of the war.

As they gained experience it was only natural that the motor firms should take more interest in designs of their own. In those days such people as Public Relations Officers were unknown and O'G was not a man to seek publicity and to explain to the outside world what his foresight had done for the country. In certain journalistic quarters the R.A.E. had a bad name and I think an unfair Press must have had some influence at headquarters. Besides O'G had disturbed the dignity of the War Office by the Nelson Touch of putting his blind eye to their orders. In modern terms, the nationalising of industry was becoming unpopular and the young aircraft industry was feeling its feet. Finally, it was decided that the R.A.E., as it was afterwards called, should be a research institution and should design no more engines or aircraft. Mervyn O'Gorman's contract was not renewed and he went into the wilderness. It must have been a bitter blow for one who had done so much for England, but he took it philosophically and devoted his energies to artistic pursuits as a talented amateur.

There is one thing that I think must have cheered him not a little. After the end of his term, Headquarters decided that a good civil servant and organiser need not be qualified as an aeronautical expert in any way. The R.A.E. was henceforth ruled by men who did what they were told without question. This went on until the Second World War was under way when at last a Director of the R.A.E. was appointed who had spent his life in the service of aviation both as a practical designer, a pilot and a scientist. O'G no doubt remembered that this man, William Farren, had been the successor in 1915 to Edward Busk and had carried on his work of aerodynamic experiments in flight.

It was in his choice of men that O'G was most happy. He collected a number of young men from the universities who helped to make a solid foundation which has enabled Britain to hold her place in the world of aeronautics.

To sum up, Colonel Mervyn O'Gorman, C.B., did as much as any man to get British Aviation away to a good start by his vision, wisdom and the sheer force of his personality. He was perhaps a bad civil servant, but he certainly was a great pioneer. He had the affection of all who worked for him and he had the satisfaction of a job well done, and this, maybe, was a greater reward than public recognition.

From Sir Geoffrey de Havilland, C.B.E., A.F.C., Honorary Fellow

MERVYN O'GORMAN did not receive adequate recognition of his work at Farnborough. There can be no doubt that he laid the foundations on which the present Royal Aircraft Establishment was built.

The former Army Balloon Factory experimented with balloons and man-lifting kites and was controlled and run by soldiers.

O'Gorman's first move was to engage practical engineers and scientists and, against opposition from the War Office, to start experimenting with aeroplanes.

I recollect the amazing subterfuges that he had to adopt in order to construct a new aeroplane. The idea was to repair or reconstruct an old aeroplane because the War Office usually refused permission to make a new one. On several occasions this lead to looking for an undercarriage or a tailplane or even a smaller unit of an old machine and using it as a basis for building a machine of entirely new design. The first B.E.

biplanes were certainly not "new" but were "reconstructed" from old wrecks.

O'G never suffered the soldiers gladly, and he could not see eye to eye with General Henderson who was his chief at the War Office. I know that it was this lack of understanding and harmony which eventually lead to O'Gorman leaving Farnborough.

He received a cruel blow when his cousin Edward Busk was killed by his B.E.2c catching fire in the air. Busk was a brilliant scientist and by his death British Aviation lost a great pioneer.

I am glad I was able to re-establish my friendship with O'G a few years ago and to visit him in his Chelsea home. He was an artist of no mean achievement, and his lacquer work and drawings were of a high order.

I remember him with affection, and will never forget that he gave me great help and encouragement in my early endeavours in Aviation.

Some personal memories of Colonel O'Gorman by Sir Geoffrey Taylor, M.A., D.Sc., F.R.S., Hon. F.R.Ae.S., and Sir Melvill Jones, C.B.E., A.F.C., M.A., F.R.S., Hon.F.I.A.S., F.R.Ae.S., were published in the April issue of the "R.A.E. News," the Journal of the Royal Aircraft Establishment, which we are privileged to reprint: —

From Professor Sir Geoffrey Ingram Taylor, F.R.S., Honorary Fellow

I FIRST met O'G about 6th August 1914, when I went, at the suggestion of Major Brancker, to ask him for a job at the Factory. As a junior member of his staff I didn't see much of him, but I quickly realised that he understood how to get the best out of us that academic scientists were capable of giving. He encouraged us in our new activities, only restraining us when we went too wildly off the track.

My chief memory of him at that time is of the occasions when I saw him in his living quarters above his office. There, out of what seemed to me a bewildering confusion of drawing boards, engines being tested, slide rules, oil and paper, was a room which at once made one feel at home, and was evidently the temporary resting place of a man of taste.

For many years my wife and I have received each Christmas one of his beautiful etchings or linocuts. We have kept them and they now form a lasting reminder of him. On one of them, showing a very picturesque and primitive village street with an open drain running down the middle, he wrote: *"It exemplifies a road of perfect safety by the Treasury method—no repairs and no traffic."*

From Sir Bennett Melvill Jones, C.B.E., A.F.C., F.R.S., Honorary Fellow

MY first meeting with Colonel Mervyn O'Gorman was when, shortly after the start of the First World War, I came here* for temporary war service, along with many other engineers and scientists whom he had attracted to work here under similar conditions. I remained here until early in 1916 and in that time acquired a great admiration and affection for him which was I believe shared by many others who worked under him, certainly by those with whom I became closely acquainted.

Two things about O'G, as we always called him, immediately impressed me. One was his great enthusiasm for the work we were all doing. Another was the way in which, when he had decided that something ought to be done, he got it done quickly, often without strict regard to existing regulations. To what extent this latter characteristic pleased the Ministry Officials under whom he was working, I do not know. But, in those days, when aviation was in its infancy and, through war stimulus, was being developed rapidly and with great urgency, it certainly did enable things to be done more quickly than would otherwise have been possible.

One example of the way in which O'G got things done as he wanted sticks very naturally in my memory. It was not until I had been working here for some months that I discovered that, officially, I was "Engineer in Charge of Fabrics"; the fabrics that in those days covered the aeroplanes. O'G was well aware that I knew nothing about fabrics and he certainly had no intention that I would ever have to work on them. It was merely that, when he engaged me, that particular post happened to be vacant and he was not in need of an additional man to work on fabrics.

Looking back on those days, I feel sure that the successful development of the R.A.E. in later years must have depended greatly on the enthusiasm for research on a great variety of subjects that O'Gorman initially infused into it. While he was in charge, the Factory, as it was then called, was concerned not only with research and the testing of aircraft; it also designed and constructed several prototype aeroplanes such as B.E.2c, the R.E.8, the F.E.2b, and the S.E.5, all of which were later built elsewhere in large numbers and played an important part in the war. But O'G must have realised very clearly that there were many aspects of science, apart from those that underlie aircraft design, which would have an important bearing on the future development of aviation. For he brought to the establishment many men who were highly competent in the many different branches of science that have a bearing on such things as the instrumental equipment of aircraft, their navigation, the operation and aiming of their armament and their radio communication. He must have been one of the first to realise how important it would be to have men competent in all these aspects of

*The R.A.E.—*Ed.*

science, who are so situated as to be closely associated with those who design and operate the aircraft.

One other characteristic of O'Gorman was the great personal interest he took in those who worked under him, and this continued long after he had left the R.A.E. and indeed almost until he died. When I last saw him, not long before he died, he was still asking anxiously for anything I could tell him about what was happening to those of my friends who had been with him here and were still living.

It may not generally be known that O'Gorman was also a very fine artist. Year after year until he died he sent to all of us, as Christmas Cards, the most beautiful etchings which he had made himself. It still gives me great pleasure to look at them from time to time, to keep alive my very happy memories of him.

From Sir William Farren, C.B., F.R.S., Fellow

IN THE DAYS of the First World War the "Factory," under O'Gorman, was a place where you made friends for life, and one of them was O'Gorman. I did not join until the beginning of May 1915, and I left in May or June 1918. Others who worked with him both earlier and for a longer time than I did are better able to give a rounded picture of his achievements. My first memories of him were formed from a rather lowly level. I remember being called to his office, and asked to sit down at his desk with him, while he took my report for the Advisory Committee for Aeronautics, and re-wrote it under my eyes. At first I felt rather indignant. I believed that my meaning was clear, and the facts beyond dispute, and it took me some time to realise that this was not what he was driving at. He wanted to put the matter, whatever it was, a bit differently, apparently with the idea either of warding off criticism or securing support. I gradually realised that he thought a lot about such problems. It seemed that he felt he was under attack. I knew nothing of the criticisms levelled at the Factory, but I soon learned.

Fate threw me into close contact with Fred Green. He was what we should now call "Chief Engineer," and I was "Chief Aerodynamicist," so I got drawn, at a rather early age, into high-level discussions. One of them fixes in my memory what I always think of as the high point of O'Gorman's career at Farnborough. Green and I were summoned into his office to meet General Brancker, and to be told that we had the offer of the French Hispano engine, then rated at about 120 horse power. Would we like to try to make a single-seater fighter with it? That was how the S.E.5 began. By the end of the War, over 5,000 had been built by the Industry.

This happened early in 1916. O'Gorman left us, under a cloud, about the middle of 1916, and I remember how strongly I felt the injustice by which a twist of fate deprived him of the thrill of seeing S.E.5 through to success. Long afterwards, when I met him more or less regularly at the Athenaeum, I hesitated to ask what he felt about all this. But from the way he spoke it was clear that, though he had no bitterness, he had been deeply wounded.

In 1954, stimulated by talks with him, I dug into the records with the help of my friends at the R.A.E. I then realised that here was the story of how a man can be made a scapegoat for the shortcomings of a policy of which he is the instrument rather than the originator. It seemed to me inexcusably unfair that O'Gorman's name should not be cleared of the implications of what happened then. Evidently he did not wish to do anything about it himself, and may indeed have preferred that the subject should be buried for ever. But on reflection, and especially in view of some short references to the tragedy which have recently appeared elsewhere, I concluded that this was a piece of aeronautical history which ought not to perish.

It seems that it was in May 1912 that the Editorial columns of the aeronautical press first contained criticism of the Government's policy for military aircraft, and of the Factory as one of its obvious and most vulnerable elements. This was stimulated by the line taken by the *Daily Mail*. *Flight* was definitely less aggressive than *The Aeroplane*. The thread running through the whole attack was that the Industry was at a disadvantage compared with the Government, owing to its relatively limited financial resources and the growing competition among its members for the small amount of business, in which, then as now, the Government was the main customer. This situation was held to be unhealthy.

Even at this date however *Flight*, in particular, emphasised that the Factory "had not the least intention of competing with industry," though it wisely warned against "the ambition of individuals." The Factory's job was to experiment, but by its very name it invited misunderstanding, and it was certainly designing and building aircraft.

In August 1912, the Military Aircraft Competition took place. O'Gorman was one of the four judges. The competition was not open to aircraft built by the Factory, but a B.E.2, designed by Geoffrey de Havilland and flown by him, went through the tests. Cody won £5,000 in prizes, but the B.E.2 apparently received the most marks, and certainly made a height record of 9,500 ft. *Flight's* comments were without bias. *The Aeroplane* (which in May had alleged that the Rules had been "framed to fit the Factory machines and to ensure that the competition was won by a B.E.") confined its remarks to wholesale criticism of the British Industry compared with foreigners, saying that "British manufacturers wanted waking up"—and quoting Kipling's "The Lesson"—"Let us admit it fairly, as a business people should."

In January 1914, *Flight*, stimulated by an interesting letter from a sub-contracting firm, which paid a tribute to the fairness and friendliness of the Factory, pointed out that the real competition which was embarrassing the Industry was that between large firms and small firms—"occupied in killing each other." *The Aeroplane*, unable apparently to decide between "deliberate knavery" and "pure ignorance" on the part of those

"who were playing the Factory's game," could nevertheless detect a change for the better. It no longer doubted the future of "the Trade," which now had little to fear. Indeed the Factory's experimental work "would keep the Trade on the move."

That the activities of this country in aviation needed "keeping on the move" was emphasised when the Naval and Military £5,000 Engine Competition was held at the Factory in May 1914. Again O'Gorman was one of the judges, but this time the Factory did not enter an engine, even outside the competition. There were 28 different types of engine, and a 100 h.p. water-cooled Green won. (It is hardly necessary to say, although it seems impossible to kill the idea, that this had no connection with our Chief Engineer). Although the Green engine won the competition, it was not satisfactory, and before long the R.F.C. was grateful for the existence of the experimental engines which the Factory had designed.

All this was before the beginning of the first War. On the whole, bearing in mind that the freedom of the Press, like all freedoms, has to be paid for, there seemed to be little cause for anxiety, and no sign that O'Gorman was personally in danger. But the War brought changes.

At the outbreak, the R.F.C. had nominally about 180 aircraft, of which 66 went to France with the Expeditionary Force. Of the remainder, only some 20 were serviceable. By the time the storm broke over O'Gorman's head in 1916, the R.F.C. had multiplied more than twenty-fold. The Industry had built, in addition to aircraft of its own design, many hundreds of B.E.2c's and F.E.2b's, and a large number of Factory engines. Later it was to build also R.E.8's and S.E.5's, the grand total being some 13,000 aircraft and 7,000 engines of the Factory's design. It is difficult not to draw the conclusion that O'Gorman was the victim of the success of the instrument which he had himself created. As an Experimental Establishment, Farnborough would probably have been accepted by a growing Industry as a valuable asset. But if it continued to design and build new aircraft, not merely flying machines to extend our knowledge and power over the air, but prototypes intended either to meet or to inspire what we should now call "Air Staff Requirements," it was clearly dangerous.

On 22nd March 1916, a Member of Parliament, Pemberton Billing, made allegations that "the officials who were responsible for deciding types of machines . . . failed either by ignorance, intrigue or incompetence to provide the best machines that this country could produce." He suggested, moreover, that "gallant officers in the R.F.C. had been rather murdered than killed." On 28th March, he gave a number of specific instances in support of his allegations, which he elaborated in words which endeavoured to distinguish between "murder, manslaughter, and criminal negligence" in events which he attributed to "official folly in high places." These accusations led directly to the appointment by the Army Council, on 7th May, of a Committee under the Chairmanship of Mr. Justice Bailhache "to enquire into the administration and command of the Royal Flying Corps with particular reference to the charges made both in Parliament and elsewhere against the officials and officers responsible for that administration and command and to make any recommendations in relation thereto."

This development had been anticipated on 30th March, by the appointment, also by the Army Council, of a Committee under Sir Richard Burbidge, "to enquire and report whether, within the resources placed by the War Office at the disposal of the Royal Aircraft Factory and the limits imposed by War Office orders, the organisation and management of the factory are efficient, and to give the Army Council the benefit of their suggestions on any points of the interior administration of the Factory which seem to them capable of improvement."

For practical purposes the functions of the two Committees were very different. The Burbidge Committee was in effect instructed to report on O'Gorman's organisation and administration of the Factory. Its report to the Army Council was dated 12th May, but was published rather later, and then along with a report dated 19th July, by the Air Board to the War Committee. This latter document, signed by Lord Curzon, in effect rejected most of the Burbidge Committee's suggestions, primarily because they were "ill-adapted to the exigencies of military organisation." But on one point the Air Board found itself able to agree with the Burbidge Committee. The Head of the Factory, whatever his title, should have "recognised ability in administration and management" and need not possess "any intimate or previous knowledge of aviation." It happened that O'Gorman's contract of engagement came to an end about this time, and it was not renewed. Indeed, by the time Curzon signed the Air Board's Report, O'Gorman had disappeared from the scene, although his successor was not appointed until 21st September.

But the allegations which led to the appointment of the Bailhache Committee and its two Reports, the Interim Report (on Pemberton Billing's allegations) dated 3rd August, and its Final Report dated 17th November, cannot be disregarded when considering the story not only of O'Gorman but of the Establishment for which he did so much. The Committee dealt first with the Pemberton Billing accusations of "criminal negligence," which was the phrase they preferred to use to describe them. After some difficulty, evidence on 15 specific instances was produced. The Committee enquired into every one of them, and the verdicts are given in detail in an 8-page Report dated 3rd August. Its conclusions were that "no-one could complain if Mr. Pemberton Billing had asked that these cases should be enquired into to ascertain whether the deaths of these men could have been prevented. But based upon these accidents, a charge of criminal negligence or murder is an abuse of language and entirely unjustified."

Its Final Report contained 25 pages, and is dated 17th November. About 4 pages are directly concerned with the Royal Aircraft Factory. The general charges which the Committee considered were, briefly, that those responsible for the administration and command

of the Royal Flying Corps placed too much reliance on the Factory, that the Factory was simultaneously competing with Industry in the design and construction of aircraft and engines, and acting as a judge of the Industry's productions, since it acted directly or indirectly as adviser to the War Office. Further, that the Factory had been a disservice rather than a service to the R.F.C. But the Committee's real task was to investigate not the Factory, but the administration and command of the Royal Flying Corps, and particularly Lieut. General Sir David Henderson, who was both Director General of Military Aeronautics and in supreme command of the R.F.C. The most significant of its conclusions was that this dual responsibility "is an impossible position for any man to fill, now that the Royal Flying Corps has grown to its present dimensions, and especially in view of its probable further growth." Its other recommendations flowed from this.

As to the Factory's relations with Industry, and its own deeds or misdeeds, and so on, it is interesting that the Committee found it extremely difficult to find any witnesses from Industry who would support the allegations which had been made in general terms both in Parliament and in the Press. Indeed, several witnesses went out of their way to express their regard for what the Factory had done to help them. Nevertheless, the Committee had no difficulty in putting its finger on the real difficulty, which was the same one as that to which General Henderson was exposed. The position of the Factory was an impossible one. Even if there was nothing in what was described as the "competitor and judge" charge, its somewhat ambiguous position was bound to lead to trouble. Similarly, if the Factory did in fact do no more than design and build prototypes of military aircraft and engines for them, it would inevitably be held by the Industry to have a favoured position in the eyes of those who made the choice between the various alternatives. The Committee concluded that the continued existence of the Factory was essential, but it should cease to design and manufacture, and should confine itself, broadly speaking, to research and associated activities.

The Burbidge Committee, while agreeing with this view, detected points in which the organisation and administration of the Factory suffered from the difficulty of trying to draw a "sharp line of demarcation between experimentation and commercial productivity." The weakness of its conclusion was that it considered that competition between the Factory and the Trade, "if reasonably administered," need not be the cause of any detrimental friction or Trade feeling. It failed to explain how the administration could be improved to secure this obviously desirable result.

While recognising the influence which these two Reports had on the careers of those in authority both in the Royal Flying Corps and in the Royal Aircraft Factory, it is hardly an exaggeration to say that the only man who suffered unjustly was O'Gorman. He passed the remaining forty years of a long life enjoying to the full his private interests and sharing them with his many friends. If it is true, as it may well be, that he had no further direct influence on the progress of British Aviation, it is equally true that, by what he did up to 1916, he created a tradition which gave inspiration to those who adopted it and have recognised it ever since. Though not in the strict sense a scientist or engineer, he understood those kinds of human beings, and their interesting and often strange points of view, as indeed he seemed to understand all those who had the privilege of being known by him. He was a great man. Only those who worked with him know how great.

THE FORTY-SIXTH WILBUR WRIGHT MEMORIAL LECTURE

THE Forty-Sixth Wilbur Wright Memorial Lecture, "Automatic Flight—the British Story," was given before the Society by Dr. G. W. H. Gardner, C.B., C.B.E., F.R.Ae.S.. on 15th May 1958, at the Institution of Mechanical Engineers, 1 Birdcage Walk, London, S.W.1. Sir Arnold Hall, M.A., F.R.S., F.R.Ae.S., President of the Society, presided, and before introducing the lecturer, presented the pricipal awards of the Society.

The President outlined the distinction between the Society's awards which are made by the Council, and the Amulree Awards—the British Gold and the British Silver Medals—which are made by a Committee representing the Society, the Royal Aero Club, the Air League of the British Empire and Government Departments, but which, by tradition are presented by the Society, with its own awards, at the Wilbur Wright Memorial Lecture. The President then made the following presentations:—

Honorary Fellowship—the highest honour the Society can confer, to: Sir Richard Southwell, M.A., LL.D., D.Sc., D.Eng., F.R.S., Hon.F.I.A.S., F.R.Ae.S.

Honorary Companionship, to: W. E. Nixon, F.C.I.S., Chairman, de Havilland Aircraft Co. Ltd., and de Havilland Propellers, Ltd.

The Society's Gold Medal—awarded for work of an outstanding nature in Aeronautics, to: Sir Sydney Camm, C.B.E., F.R.Ae.S., Chief Designer and Director, Hawker Aircraft Ltd., "for his outstanding achievements in aircraft design and development."

The Society's Silver Medal—awarded for work of an outstanding nature in Aeronautics, to: P. B. Walker, C.B.E., M.A., Ph.D., F.R.Ae.S., Chief Scientific Officer and Head of the Structures Dept., R.A.E., "for his distinguished contributions to aircraft structural integrity."

The Society's Bronze Medal—awarded for work leading to an advance in Aeronautics, to: D. Williams, D.Sc., F.R.Ae.S., Deputy Chief Scientific Officer, R.A.E., "for his contributions to the theory of aeroelasticity."

The British Gold Medal for Aeronautics—awarded for outstanding practical achievement leading to advancement in Aeronautics, to: S. D. Davies, B.Sc., F.R.Ae.S., Managing Director, Dowty Fuel Systems Ltd. (formerly Chief Designer, A. V. Roe and Co. Ltd.), "for his outstanding practical work in the design and development of delta aircraft."

The British Silver Medal for Aeronautics—awarded for practical achievement leading to advancement in Aeronautics, to: W. H. Lindsey, M.A., F.R.Ae.S., Technical Director, Armstrong Siddeley Motors Ltd., and W. F. Saxton, M.B.E., Deputy Managing Director, Armstrong Siddeley Motors Ltd., "for their practical contributions to the development of aircraft gas turbines."

The Wakefield Gold Medal—awarded for contributions towards Safety in Aviation, to: W. Tye, O.B.E., B.Sc., F.R.Ae.S., Chief Technical Officer, Air Registration Board, "for his great contribution to the airworthiness of British civil aircraft."

The R. P. Alston Medal—awarded for practical achievement associated with the Flight Testing of Aircraft, to: Mrs. Anne Burns, B.A., a Principal Scientific Officer, Structures Dept., R.A.E., "for her practical contributions to aircraft safety as a flight test observer."

The N. E. Rowe Medal (21-26 Age Group)—awarded for the best lecture given before any Branch of the Society by a member of a Branch, to: P. A. Champion, B.Sc., Aerodynamicist to the Supersonic Wind Tunnel, Bristol Aircraft Ltd., "for his lecture, 'Some Factors Involved in the Supersonic Wind Tunnel Testing of Models.'" Mr. Champion was unable to be present to receive his Medal. No award in the Under 21 years of age Group was made.

The President then introduced the Lecturer, Dr. G. W. H. Gardner, who is an Ulsterman, and who graduated with a First Class Honours Degree in Mechanical Engineering from Queen's University, Belfast, serving his engineering apprenticeship with Messrs. Harland and Wolff. He joined the Scientific staff of the Royal Aircraft Establishment in 1926, working on a variety of aeronautical problems including automatic pilotage, pilotless aeroplanes, navigation, bombing and the measurement of physical quantities in flight. He has held a number of appointments at the Air Ministry, London, and at the Ministry of Supply, Headquarters Branches; he was Head of the Physics and Instruments Department from 1943 to 1945, Head of the Guided Weapons Department from 1945 to 1947, Director and later Principal Director of Guided Weapons (Research and Development) and Director-General of Technical Development (Air).

In 1955, Dr. Gardner was appointed Director of the Royal Aircraft Establishment, his present position. He is a Member of the Council of the Society and first Chairman of the Society's newly-formed Guided Flight Section.

The Forty-Sixth Wilbur Wright Memorial Lecture

Automatic Flight—The British Story

by

G. W. H. GARDNER, C.B., C.B.E., D.Sc., M.I.Mech.E., F.R.Ae.S.
(Director, Royal Aircraft Establishment)

Introduction

I feel deeply honoured to have received the Society's invitation to deliver the 46th Wilbur Wright Memorial Lecture. I undertook the task with humility in the light of the illustrious company who have preceded me but, more particularly, because of the greatness of the contribution of Wilbur Wright whom we honour tonight which, together with that of his brother Orville, continues to provide a tremendous inspiration to all concerned with aeronautics.

In considering the choice of subject for this lecture, it was tempting to discourse on the possible future potentialities of aircraft, manned and unmanned and, in particular, on ways in which a vigorous research activity could create new and valuable realisations hitherto unsuspected. This could have been highlighted by descriptions of some of the interesting work being done and notable contributions made by the staff of the great Establishment with which I have the honour to be associated. However, Sir Arnold Hall's "Sir Sefton Brancker Memorial Lecture" given to the Institute of Transport a few years ago[1] was an excellent one of this kind and, more recently, my colleague Mr. M. B. Morgan followed a somewhat similar theme in his Chadwick Memorial Lecture[2]. Accordingly, and in view of the formation during the past year of the Society's Guided Flight Section, of which I have the privilege of being the first Chairman, I decided to choose a subject which has some relation to guided flight, yet had its origin before the Wright Brothers flew, namely the British story of the evolution of automatic control of flight. Much of this story has not been told before and I hope that this fact will compensate, to some extent, those readers who would otherwise deplore another historical review.

It is hoped that the interest of the story will not be confined to the historical aspect; it is felt that some interesting pointers emerge and that the story provides one example from which some deductions flow relating to the place of research in Government establishments in relation to the overall aeronautical activity in this country.

The aim of achieving fully automatic flight has, throughout the years, strangely but powerfully fascinated those engaged in its pursuit. The evolution from early failure to eventual success includes much drama and excitement and seems worth the telling. Parts of this story have been told before in the Technical Press and notably in 1937 in a lecture to this Society by Meredith and Cooke[3], and later in 1949 by Meredith[4], who made outstanding contributions to the science and art of automatic pilotage. In this paper the attempt will be made to sketch the main features of the whole story coherently up to recent years, when the application became widespread in the control of aircraft and when, together with the advances in the state of the art in other directions, the guided missiles and pilotless targets that we now know became possible.

Much of the story concerns attempts to develop pilotless aeroplanes, many of which were manoeuvred in response to commands transmitted by radio, but limitations of space have decreed the omission of the radio part of the story.

F. S. Barton and G. R. Joyce were mainly responsible for the successful evolution of radio control equipment and, although the radio story is omitted, it should be appreciated that the radio problems were just as vital as any other in the development of radio-controlled aircraft. Lack of space has also decreed the omission, with one exception, of references to achievements in this field in other countries.

Earliest Ideas

The first British-proposed automatic flight control was in 1891 by Sir Hiram Maxim, who intended to secure longitudinal stability of his proposed aeroplane by the automatic actuation of bow and stern elevators in response to disturbances detected by a gyroscope. As his aeroplane was wrecked in an attempt to take off this proposal came to naught. The next contributor was T. W. K. Clarke, who described some of his work in a paper delivered to the Aeronautical Society in 1912[5]. In this paper Clarke analyses methods of stabilising an aeroplane and describes an automatic aileron control. He was clearly well aware of the pitfall of trying to secure too high a degree of stability by built-in means such as dihedral and stated that the safest machine and the easiest one to control would be that in which the "equilibrium" is neutral. In his paper he discusses some pros and cons of various sensors, such as the pendulum, magnetic compass and the gyroscope, and recognises the merit of influencing an otherwise free gyroscope by spring restraint, or by pendulum action. He pointed out very clearly the tendency of the simple pendulum to indicate the direction of the apparent vertical and hence its unsuitability as an instantaneous detector of direction in pitch. He constructed a roll auto-stabiliser or damper which contained a number of

features in use today. It is most unfortunate that Clarke's work did not proceed beyond the laboratory stage.

1917 Pilotless Aircraft Experiments

The earliest practical attempts in this country to achieve automatic flight were stimulated by the prospect of using uninhabited aeroplanes as missiles and for other military purposes. The need for automatic pilots in manned aeroplanes did not again arise until later.

According to the late A. M. Low he, when serving in the Army, was invited by General Caddell, in association with Sir David Henderson, to consider the application of "wireless" to the remote control of aeroplanes in order that they could be used as flying "bombs" or "torpedoes." Low was given some staff to help him and the team was first located at Brooklands and later at Feltham, Middlesex, where the unit was named the R.F.C. Experimental Works.

Low first fitted his wireless gear to an aeroplane of unknown origin and tried unsuccessfully to fly it at Upavon. The Royal Aircraft Factory was then asked to design a suitable aeroplane.

A British patent specification No. 244258 in A. M. Low's name was accepted on 10th December 1918; it is clear that this patent was based on the work commissioned earlier by the Army, but the application was delayed for security reasons. The patent depicts an aeroplane designed at the Royal Aircraft Factory (R.A.F. Drawings A.11493 and A.11494). The invention consisted of the application to this aeroplane of an explosive or incendiary charge, wireless gear as described in Low's patent specification number 244293, and "actuating" or servo gear as described in his patent number 195101.

Low records that the pilotless aeroplanes with which he was concerned were developed to attack Zeppelins and to bomb enemy railways and camps from a distance. To conceal the purpose of the development, the description "aerial target" was used.

The aeroplane used in the further tests to be described was the one subsequently shown in Low's patent application (Fig. 1). The weight was about 500 lb. and the wing span 20 ft. A 35 h.p. horizontal two-stroke opposed twin A.B.C. engine, designed by Granville Bradshaw, was used.

No attempt to develop an automatic pilot was made; manoeuvres were to be effected by full application of the otherwise fixed rudder and elevator in response to radio signals. Provision was also made to adjust the engine throttle.

It was decided to launch the R.A.F. aeroplane by mounting it on a fairly light truck with four wheels arranged to run on rails, set at such an inclination to the horizontal that the component of the weight of the truck rather more than balanced the friction. A length of 100 feet of inclined rail was provided and connected by a smooth curve to a horizontal run of 50 feet. This installation was laid down at Northolt in preparation for the next trials.

Also early in 1917, before these trials, important

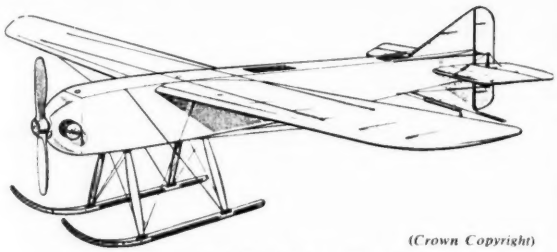

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FIGURE 1. R.A.E. pilotless aircraft—1917.

aerodynamic characteristics of the aeroplane were measured at the Royal Aircraft Factory in a wind tunnel. The following accounts of the trials at Northolt are based on Royal Aircraft Factory reports.

The first was attempted on 6th July, 1917. The machine was delivered from Farnborough to Feltham on 5th June 1917 where the wireless gear was fitted and tested on the ground. The machine was then sent over to Northolt where it was assembled and the W/T gear fitted and tested. According to the official report of the test, the machine rose from the carriage about half way down the track and immediately began to climb at a very steep angle. This angle increased until the nose was pointed vertically upwards. The machine then turned over on its back and dived vertically to the ground about 30 yards to the right of the track. The "elevators down" signal had been sent and may not have been received, as there was no appreciable flattening out of the climb. The accident was thought to be due almost certainly to the machine being more tail heavy than was expected from the model tests. It is possible that the real cause was the large overshoot to be expected in an uncontrolled transition of this kind.

The next test was held on 25th July 1917 and ended in a crash because a change in tail setting of two degrees, as compared with the previous trial, trimmed the machine at a speed considerably in excess of that which it could reach in the length of the track.

The next trial on 28th July, 1917 with an intermediate tail setting ended in failure because the engine cut-out halfway down the track. It continued firing in rather an irregular manner and the machine which had, at halfway, attained a speed of nearly 40 m.p.h. steadily decelerated. It left the end of the track at about 30 m.p.h. and the undercarriage broke up almost immediately. When the machine was travelling at its highest speed, that is halfway down the track, it was still standing level on its supports which indicated that the tail setting was fairly nearly accurate.

Although three additional machines were available, no further flights were attempted. This series of trials had demonstrated the difficulty of achieving successful take-off and climb with an elevator fixed in a predetermined position.

Important Developments, 1920-1925

In 1920 interest again grew in the possibilities of pilotless aircraft and a programme of work was initiated aimed at development of:—

1. An "ammunition carrier" which was to be a gyroscopically controlled aircraft capable of flying on a steady course at a constant speed for a given distance.
2. An "aerial target"—an inherently stable aircraft capable of flying up to a range of 20 miles.
3. An "aerial torpedo"—to be dropped from aircraft and capable of flying under W/T control up to a range of 10 miles. Two versions were to be developed, one powered and one without an engine.

The "aerial torpedo" was abandoned after some model size gliders had been tested and during the next few years a single programme was aimed at the satisfaction of the first two requirements.

An aeroplane was designed with the following characteristics (Fig. 2):

Total weight	630 lb.
Ceiling	11,300 ft.
Speed at 6,000 ft.	103 m.p.h.
Span	23 ft.
Length	18 ft.
Engine	Ounce, Siddeley Deasay (45 h.p.)
Payload (warhead)	200 lb.

Work was started in parallel on the development, by G. L. Smith and P. S. Kerr, of a simple automatic pilot, consisting of a gyroscopic rudder control and a crude control of elevator in response only to height by means of an aneroid and an air log to control range. The radio equipment development was undertaken by the Instrument Development Establishment at Biggin Hill. The personnel of this Establishment were moved to Farnborough in April 1922 and all subsequent work was done at the Royal Aircraft Establishment.

In October 1921 a landmark was reached when a Bristol Fighter (not unmanned) equipped with a simple gyro rudder control was steered automatically in response to radio signals transmitted at ranges up to eight miles from the ground at Farnborough.

This seems to have been the first occasion in this country that an aeroplane was actually manoeuvred automatically in response to commands transmitted by radio.

In the middle of 1922 attempts to launch and fly the pilotless target began under the supervision of R. McKinnon Wood, then Head of the Aerodynamics Department at R.A.E. and more recently Chairman of the London County Council. The earlier tests were made without wireless control, prescribed manoeuvres were planned instead in response to signals given by an engine-driven programme switch.

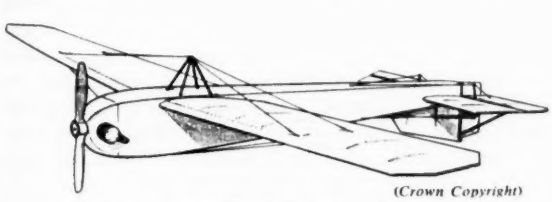

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FIGURE 2. R.A.E. pilotless aircraft—1921.

The basis of the directional control, developed in the course of these tests, was a free Whitehead torpedo type gyroscope continuously spun with compressed air (Fig. 3A). The axes of the gyroscope rotor and its two supporting gimbal rings were mutually perpendicular and the system was installed with the rotor axis horizontal in the plane of symmetry of the aeroplane. The inner gimbal ring axis was also horizontal and perpendicular to the rotor axis, while the outer gimbal ring was vertical. Accordingly, angular movement of the outer gimbal ring relative to the aeroplane was a measure of yaw and caused through a pneumatic piston valve the operation of a pneumatic servomotor attached to the rudder. The elevator was held against a stop at the estimated angle to trim on the climb. An aneroid caused the elevator to move away from the stop when the pre-set height was reached and to constrain the aeroplane to fly at that height. The rudder control was initially "bang-bang" but "follow-up" or "feedback" was soon introduced, thereby providing rudder movements proportional to the disturbance in yaw.

The first two flights were attempted by mounting the aircraft on a simple trolley designed to run on rails laid on the deck of the aircraft carrier H.M.S. *Argus*. These two attempts on 31st August 1922 and in September 1922 were unsuccessful as in each case the aircraft crashed into the sea, once because the aircraft was not released from the trolley at the right time and, on the other occasion, after a violent lateral oscillation had built up during the climb. After these two failures, which were believed to be due to some extent to the overshoot during the transition from horizontal launch to climb with fixed elevator, it was decided to launch into the climb by using an inclined catapult. This arrangement demanded correct ship plus wind speed to give the required angle of climb. Motive power was supplied by a large bag filled with water which, when tripped, fell vertically into the sea and caused the aeroplane to accelerate up the inclined rails. The catapult was mounted on the bow of a destroyer, H.M.S. *Stronghold* (Fig. 4).

The first two flight experiments from *Stronghold* exhibited satisfactory launches but in each case a lateral oscillation of increasing amplitude built up during the climb, but was damped when the aircraft levelled out at 2,000 feet. The explanation of the violent oscillations on the climb was discovered by F. W. Meredith. This was the effect of tilt of the gyroscope axis in the plane of symmetry relative to the fore and aft axis of the aeroplane. Any such tilt caused the outer gimbal ring to respond to roll; if the tilt were up in front, top rudder was applied in response to roll; and vice versa. Meredith demonstrated in flight in a Bristol Fighter, and Gates confirmed mathematically, that a small downward tilt could destabilise the lateral motion, and this provided the explanation of the tendency to unstable flight experienced during the climb in the pilotless flights.

In the next pilotless flight, the gyroscope was installed so that its rotor axis was athwartships at

launch. (Fig. 3B). This flight, on 22nd February 1924, exhibited, as expected, a steady climb but after flattening out at 2,000 feet, the subsequent behaviour was far from steady. After five and a half minutes of wild manoeuvre, the aeroplane collided with the tail of the seaplane carrying the camera, and dived into the sea. The wild behaviour was attributed to the inner or horizontal gimbal ring of the free gyroscope having toppled so far as to produce instability, and the final disaster occurred because the inner gimbal ring had reached the limit of free motion. Accordingly, a self-righting or anti-topple mechanism was designed to retain the rotor axis at a fixed angle in relation to the outer gimbal ring. At the same time, means were introduced to enable the gyroscope to be precessed in order to change course. These arrangements enabled the gyroscope to be installed with the rotor axis at all times in the plane of symmetry of the aeroplane. This arrangement permitted the use of some upward tilt of the rotor axis, thereby enhancing the damping of the lateral oscillation. (Fig. 3C).

Flights in the Bristol Fighter confirmed the merits of these arrangements and showed that, with the precessional method of turning, the additional lateral damping obtained by tilting the rotor axis proved very useful and good turns were effected up to a speed of 16° per second without excessive oscillation, either at the start or the end of the turn.

A further pilotless flight on 6th June 1924, proved the satisfactory behaviour of the control and it was then decided, for subsequent flights, to apply wireless control in place of clockwork to direct the flight plan.

SEVENTH EXPERIMENT—3RD SEPTEMBER 1924

The seventh flight was made from H.M.S. *Stronghold* on 3rd September 1924. Radio control gear had been fitted to give four signals, namely, turn to port, fly straight, turn to starboard and cut out engine. The aeroplane took off without any appreciable oscillation and after five or six minutes, six signals in all were transmitted and obeyed. However, after about 12 minutes flight, the engine cut-out unexpectedly, and the aeroplane glided down and landed with little damage in the sea.

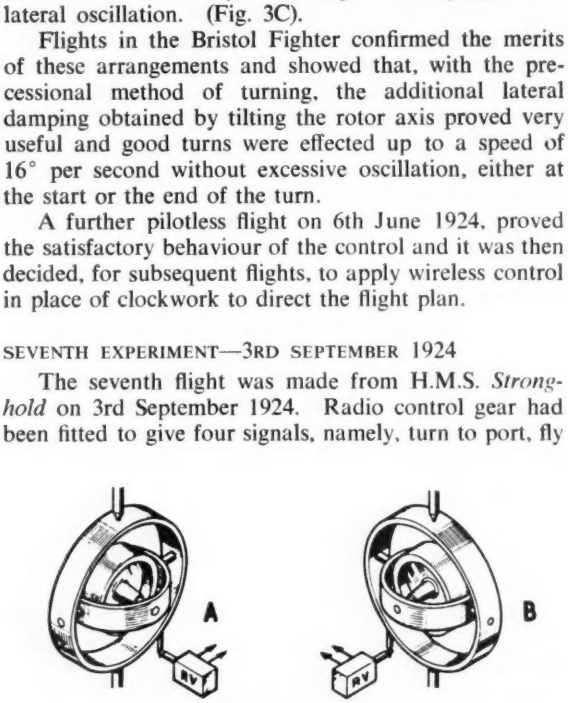

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FIGURE 3. Evolution of first R.A.E. automatic pilot directional gyroscope.

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FIGURE 4. H.M.S. *Stronghold*—inclined catapult.

Three more flights were made between September 1924 and February 1925. On the last of these the aeroplane flew for 39 minutes during which time 43 signals were sent and acted upon. The aeroplane was picked up practically undamaged.

It was considered that the problem of this aeroplane had been solved. The more recent failures had not been due to any fundamental weakness but were accidents which could be prevented by more attention to detail. The equipment seemed more reliable than the engine, which remained a source of anxiety.

No information as to the range of the W/T control was gained, because it far surpassed the visible range, but there was no doubt that with a transmitting set such as was used on this occasion, the range was quite adequate for the purpose of high angle firing practice.

It was considered that as a target for high angle firing, the machine had considerable possibilities but no decision was forthcoming to use the aircraft in service.

THE R.A.E. PILOT'S ASSISTER

By applying the lessons learnt during these flights Meredith and Cooke, in 1925, evolved an automatic pilot embodying features which were to be used in combination for the next 20 years in various British automatic pilots. The principal additional feature not already described which was introduced at this time was means whereby the attitude of the aeroplane to the apparent gravitational field controlled the precession of the gyroscope about the inner gimbal ring axis; the gyroscope was converted thereby into a long period pendulum (Fig. 3D). Instead of constraining the inner ring to remain in a fixed relationship to the outer ring, the system was placed out of balance with respect to the vertical axis and accordingly, precession of the inner

gimbal ring occurred in response to longitudinal acceleration. By fitting a detector between the inner gimbal ring and the aircraft, pitch relative to the gyroscope was sensed and elevator was applied to correct this. By this means, it was found that the aeroplane was constrained to fly remarkably accurately at any required pitch attitude. This attitude was changed at will by superimposing about the vertical axis of the gyroscope, a torque supplied by a spring which could be varied at will. A valuable feature of this type of elevator control is that change of flight attitude does not persist with change of elevator required to trim. Any instantaneous demand for such a change results in a sympathetic change of pitch to the extent required to apply the change in elevator angle, but this change in pitch immediately causes the horizontal ring of the gyroscope to precess and the attitude to recover to its former value. Here then, was a complete automatic pilot based on one gyroscope, providing a stiff control in yaw and pitch and some enhancement of the inherent roll stability of the aircraft. This automatic control was known as the R.A.E. Pilot's Assister and was fitted and used successfully in many large military and civil aircraft.

First Successful Radio-Controlled Pilotless Flight

It is of interest that during the early 1920's experiments were conducted under the sponsorship of the Bureau of Ordnance of the United States Navy aimed at proving the possibility of flying a pilotless aeroplane under radio control. An automatic pilot and radio receiving equipment were installed in an N.9 seaplane and after tests with a safety pilot aboard, a flight without a pilot on board was made on 15th September 1924 from Dahlgren. After a bag of sand had been lashed securely to the pilot's seat to compensate for the pilot's weight, the seaplane was pointed into wind and the throttle was opened by radio control. The seaplane took off smoothly and remained airborne for about 40 minutes, during which time more than 50 radio signals were sent and the majority answered correctly. Trouble was, however, experienced from time to time through wrong response to one turn signal and for a time it was found impossible to operate the throttle control. During some manoeuvres just before the end of the flight, the seaplane lost a lot of height and it was considered advisable to attempt a landing. The signal was sent to close the throttle, but it was seen that the landing would be a poor one and a further signal was sent to open the throttle to make another try. Before the increased engine power could take effect, however, the seaplane forcibly struck the water and it seemed that the base of the float had been damaged. The seaplane rose to a height of about 50 feet, and a satisfactory landing was effected by easing off the throttle about one minute after the first attempt. Immediately after landing the seaplane began to sink slowly.

This is the first record in the United States of a comparatively successful pilotless controlled flight from the controlled take-off through a satisfactory controlled flight of 40 minutes to a hard landing which damaged the aeroplane. The flight fell short of perfection by virtue of some misbehaviour of the radio and control gear and of the rather poor landing. It is of interest that only 12 days earlier, on 3rd September 1924, the seventh of the contemporary series of flights in the U.K. was, in some respects, even more successful than this American flight. The British flight fell short of perfection only in that the engine failed after 12 minutes, but the control was such that it was possible to make a nearly perfect landing on the sea. The British aeroplane had never been flown by a human pilot and was launched by a catapult. The American aircraft had been flown extensively by a human pilot and was capable of taking off under its own power.

The author is most grateful to Rear-Admiral D. S. Fahrney, U.S.N. (Retd.) for supplying, and to the United States Navy for permission to publish, the information about the American flight. Rear-Admiral Fahrney and the author are agreed that comparable successes in the art of radio controlled pilotless aircraft were achieved by the British flight on 3rd September 1924 and the American flight on 15th September 1924. In neither country, however, was the success followed by an immediate practical application. Adoption by the Services in each country for target purposes did not take place until much later dates, immediately following successful demonstrations of more advanced pilotless aeroplanes on 9th September 1932 in U.K. and on 23rd December 1937 in U.S.A. The most interesting feature about the earlier two flights is that they took place within a span of 12 days, although the developments had proceeded completely independently, each without knowledge of the other.

The Impact of Aerodynamics on British Development

At a much earlier stage than appears to have been the case in any other country, mathematical analysis of the dynamics of the controlled motion of an aeroplane played a large part in the development of the automatic pilot and of pilotless aircraft. In 1903, Bryan and Williams, for the first time, applied the techniques of Routh to aircraft dynamics. In 1924, S. B. Gates, for the first time, extended Bryan's equations to include automatic control terms when he investigated the stability and response of an aircraft with automatic directional and height controls.

Among other things, Gates stressed that the achievement of good stability was not necessarily adequate but that, in addition, good stabilisation was essential in the sense of constraining the amplitudes of the motions to tolerable levels. Until modern computational aids became available, however, it was extremely laborious to calculate completely the disturbed motions of an aeroplane and most analyses were confined to the determination of damping factors and frequencies only.

It was, however, the discovery and understanding of the effect of tilt more than any other which permitted a great simplification of a number of later British

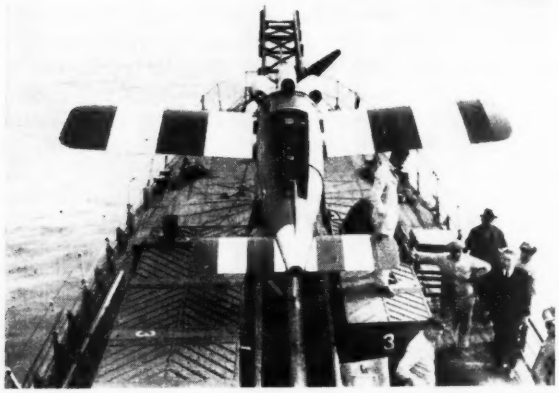

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FIGURE 5. The Larynx pilotless aeroplane.

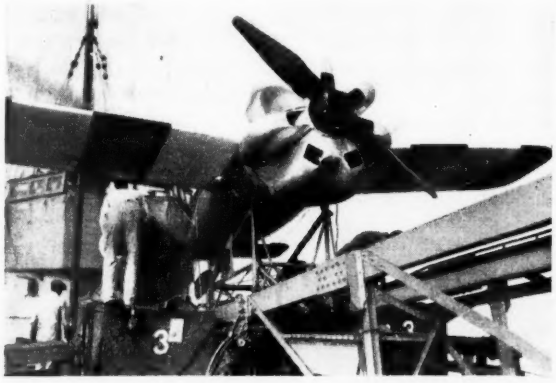

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FIGURE 6. The Larynx.

automatic pilots. By applying this trick, which could be done without the slightest complication, yaw, plus roll and pitch could be detected by one gyroscope and in response, operation of rudder and elevator could provide adequate stabilisation for most purposes. At a later date, when steering through the operation of the ailerons became the vogue, a similar trick was used again in the Mk. 8 automatic pilot. In this case, aileron and elevator were applied in response to detection of yaw, plus roll and pitch by one gyroscope.

"Larynx"

Progress in the art of automatic pilotage offered the possibility at this time of developing an unmanned bombardment weapon. In September 1925, work was started on the objective of developing a weapon with a range of 300 miles and capable of carrying a warhead weighing 250 lb. The automatic pilot was based on the same principles as the R.A.E. Pilot's Assister and embodied monitoring of the automatic pilot by a magnetic compass, as proposed originally by McKinnon Wood and Meredith. This led to the decision to omit radio control owing to its susceptibility to jamming and instead to rely on the aeroplane flying on a course to a range and at a height all predetermined by using a compass and aneroid monitors of the automatic pilot and an air log to determine distance flown. The error which would be achieved at the target was clearly a function of the inaccuracy of wind determination but some analysis revealed that this dead-reckoning method of navigation would introduce not intolerable errors. Incidentally, L. C. Bygrave recognised the merit of the compass-monitored gyro idea as a means of providing an improved compass and it is believed that this was the origin of gyro-stabilised compasses for aircraft throughout the world.

The means described enabled the aeroplane to be launched in any direction required to take advantage of the natural wind and the compass control would cause it to turn to the prescribed heading. The gimbal system was arranged to be locked during the launching acceleration in such a position that the correct elevator and rudder to trim were applied as soon as the aircraft left the catapult. Power for operating the automatic pilot was supplied by an engine-driven air compressor.

The aeroplane was designed *ab initio* as a pilotless aeroplane (Fig. 5). A 200 h.p. Lynx engine was selected and a low-drag cowling was designed (Fig. 6). The name "Larynx" was an abbreviation of "long range gun with Lynx engine." The aeroplane was a clean mid-wing monoplane with circular fuselage tapering in diameter towards the rear. Extensive wind tunnel tests were done and the speed was predicted to be in the region of 193 m.p.h. Two compasses were fitted, the second as a safety device to detect if the aeroplane had turned beyond acceptable limits to either side of the prescribed course, in which event the engine cut-out switch would be operated.

It was arranged to plot the course of the aircraft by making direction-finding observations on a transmitter carried in the aircraft. Experiments were carried out in the Bristol Channel and the direction finding stations were situated along the north coast of Devonshire and Cornwall. It was arranged that the pitch of the interrupted C.W. transmission should be used as a measure of engine speed and at intervals the signals were interrupted by the air log, thereby enabling distance and speed to be readily deduced. This may have been the first application in the U.K. of the use of radio telemetry from aircraft.

As mentioned earlier, the gyroscopic pitch control was monitored by an aneroid and it was thereby possible, as the result of a simple adjustment, immediately prior to flight, to set the control to cause the aeroplane to fly level at any required height within its capability. A cordite-operated telescopic tube catapult was designed and built in the R.A.E. in such a way that it could be mounted on the bows of the destroyer H.M.S. *Stronghold*. Twelve aircraft and many items of auxiliary gear were also built at the R.A.E.

The first trial was planned to take place from Swansea Bay in the Bristol Channel to a point near Cape Cornwall. The launch, on 20th July 1927, was successful but, after a few minutes, mechanical failure of the compressor drive brought the flight to a premature end.

The second trial took place on 1st September 1927

over the same course in the Bristol Channel. Some sideslip was acquired immediately after launch and, as a result, the aircraft did not climb quickly enough to prevent the weight on the end of the aerial striking the sea and breaking off. Accordingly, it was not possible to track the aircraft but wreckage was recovered 11 days later off the coast of Cornwall and it was estimated that the aircraft had crashed close to its "target." There was much concern among the local fishermen regarding the fate of the pilot of the aeroplane and owing to the very secret nature of the project, it was not possible to ease their minds by telling them the truth. However, they were persuaded to release the wreckage which was brought back in the guard's van of a train to Farnborough.

It was considered after this flight that the aircraft had insufficient stability on the climb to overcome, without great risk, slight divergences from the correct attitude. Accordingly, extensive stability calculations led to a decision to increase the dihedral from 0° (unloaded) to 5°, and to increase the fin area by 20 per cent.

Further stability calculations revealed that the distribution of damping among the lateral motions during climbing flight was powerfully affected by extremely small changes in the angle of tilt of the gyroscope, and that the choice of this angle was much less critical in association with the new values of rolling and yawing moment due to sideslip.

The third attempt was completely successful and Fig. 7 shows the plot of the track as given by the four D.F. stations.

The fourth flight was planned to take place over West Bay in the English Channel from near Portland Bill to near Start Point where a drifter was anchored to observe the end of the flight. The air log was arranged to cause titanium tetrachloride to be ejected at frequent intervals during the last five miles of the flight to facilitate observation from the drifter. Just before the launch the engine was running at full throttle and some last minute adjustments were being made by a junior member of the R.A.E. team. At this point, the trolley carrying the aircraft collapsed forwards and the aircraft crashed on the catapult. The propeller disintegrated, the container of titanium tetrachloride burst and the R.A.E. junior was projected by the tailplane over the edge of a 6 ft. high packing case head first onto the steel deck. The destroyer was steaming into wind and much of the titanium tetrachloride smoke went down the ventilating shafts and found its way throughout the ship, depositing hydrochloric acid on the way. The R.A.E. junior was fortunate to survive to tell this story in this Wilbur Wright Lecture.

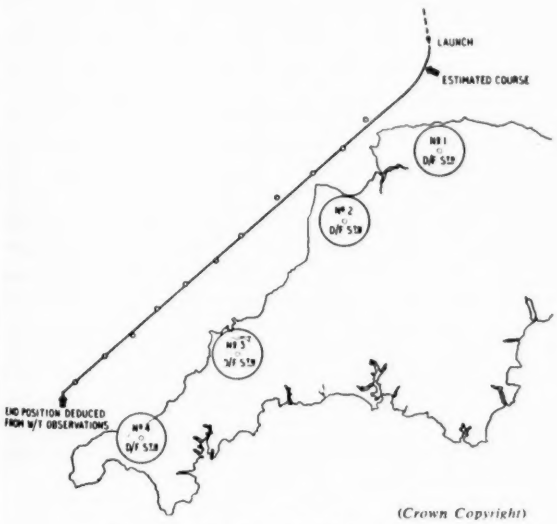

FIGURE 7. Track of third Larynx flight.

The fifth flight was over the same course and at the appointed time, after a successful launch, the first puff of smoke was seen, as hoped for, five miles from the target and on track. Immediately after, the Larynx started and continued to turn to the left and lose height and finally struck the sea about five miles from the drifter. It was thought that some of the smoke was sucked into the fuselage through the orifice at the rear and caused shorting of certain electrical contacts.

A final trial in the U.K. was planned to test a land catapult which was to be used for further trials abroad. The catapult was installed on Portland Bill. The controls were set to cause the engine to "cut" only a few miles from land in the hope that it would be possible to observe for the first time the pre-arranged spin into the sea. This trial was successful.

LARYNX TRIALS IN IRAQ

Towards the end of 1928 it was decided that R.A.F. personnel should conduct trials, with warheads fitted, in desert country in Iraq in 1929. P. A. Cooke of R.A.E. was appointed as the officer-in-charge of all technical work. Three R.A.F. officers, F./Lt. L. M. Iles, A.F.C. (now Air Vice-Marshal Iles), F./Lt. C. J. Sims, D.F.C., and F./Sgt. (now Wing Commander) R. B. Cleaver were attached early in 1929 to the R.A.E. to take part in the preparation for the trials. A cordite catapult and five "Larynx" aircraft, together with all the special equipment required were despatched from R.A.E. to Basrah; these arrived in Iraq in July 1929. It was decided to install the catapult at the edge of Shaibah Airfield, the station of No. 84 (Bomber) Squadron. Two forts, Bussiyah, distant 100 miles and Sulman, distant 200 miles, were to be used as bases from which to fix the ends of the flights.

It is interesting that only one fitter and four aircraft hands were asked for and allotted to assist the officer party from the U.K. in the preparation for, and conduct of, the trials. No earlier preparations had been made in Iraq and, apart from the making of a concrete base for the catapult, only minor assistance was given to the main party.

Many difficulties had to be overcome and the heat precluded any strenuous afternoon work but it is remarkable that so much was accomplished by so few in so short a time. Cooke and Iles arrived in Shaibah on 19th July, Sims and Cleaver on 5th August. The first Larynx flight took place on 31st August, the fifth

on 3rd October. Everything was dismantled and put on rail before the U.K. party left Iraq on 24th October.

The first three aircraft were launched successfully and, in each case, the aircraft crashed on or very near the intended track but, after flying only part of the distance (approximately 200 miles).

Engine seizure was suspected and the presumed cause was overheating of the lubricating oil. It was decided before the subsequent flights to fit a simple oil cooler, to ventilate the space surrounding the oil tank and system, and to cause the Larynx to fly at 8,000 feet instead of 3,000 feet.

The fourth test failed due to premature operation of the catapult safety valve and the aircraft was extensively damaged.

The fifth "Larynx" was launched satisfactorily and was last seen flying steadily at 8,000 feet, on track, 22 miles from the start, and all search for the wreckage was abortive.

	Track error	*Distance*
First flight	0	27 miles
Second flight	3°	60 miles
Third flight	2°	35 miles
Fifth flight	0	More than 22 miles

CAUSE OF LARYNX FAILURES IN DESERT

After further examination of engine parts in the U.K. and after extensive experiments to determine the likely effect of the high temperature on the fuel and oil systems, it was finally concluded that a more likely cause of the premature engine failures was vapour locks in the fuel system.

Although these trials were not conclusive, it is clear that with a very small amount of development, this bombardment weapon could have been available to the Services in the early 1930's. At extreme range of 300 miles the accuracy would not have been high, except when the intervening wind could be accurately forecast. It could, of course, be used in all weather conditions.

It is of historical interest that the German V.1 first launched against Britain on 13th June 1944 and followed by over 3,000 in the first five weeks of the bombardment, was based on the same control and navigation concept as the Larynx tested in Iraq in 1929.

DEVELOPMENT POSSIBILITIES OF LARYNX

All practical work on the Larynx ceased after the desert trials but, during the ensuing years, the position was reviewed from time to time with the object of determining the possibilities of either higher performance or, cheaper cost in production. At one stage an ingenious simple engine, operating on the swash-plate principle, was proposed by Mr. P. Salmon of the R.A.E. and early in 1935, Dr. A. A. Griffith proposed "A simple form of constant pressure internal combustion turbine of low compression ratio and thermal efficiency but of simple construction and light weight. The working fluid for this turbine would be the air drawn from the boundary layer". Ease of manufacture was of prime importance, while range was a secondary consideration. The following gives the proposal in more detail: "The element of the power plant through which the boundary air would pass in the order given, comprises a four-stage axial flow compressor compressing to about 1·65 atmospheres with an efficiency of 80 per cent; a combustion chamber in which the air would be heated to about 600°C by jets of burning fuel directed against the air stream, a two-stage axial flow reaction turbine mechanically coupled to the compressor and taking enough power out of the hot compressed air to drive the compressor and any auxiliaries, but not doing any other work and, a rearwardly pointing orifice in which the remaining energy of the air would be converted into kinetic energy for jet propulsion. No airscrew would be used."

It was estimated that, in this way, an aeroplane of 1,000 lb. total weight could have a top speed of about 500 m.p.h. at 15,000 feet and a minimum catapulting speed of about 100 m.p.h. The compressor and turbine rotor diameters would not exceed 8 in. over the blade tips. By March 1936, however, F./Lt. Whittle had already started the constructional work on his scheme and experiments were expected to begin at Cambridge in October 1936. It was therefore decided that no work should proceed on Griffiths' scheme pending the results of the Cambridge tests and indeed, no further consideration was given after this date to the possibility of developing an improved Larynx.

Renewed Interest in Target Aircraft—Fairey Queen

The considerable "bomb versus battleship" controversy which had persisted for some years resulted in 1930 in the decision by the Air Staff to attempt to develop a target which would realistically simulate bombing and torpedo attacks on ships. It was hoped that the results of Naval engagements of targets of this kind would resolve the competing claims, on the one hand of the Air Ministry, based on achieving a high percentage of "hits" on the (undefended) target ship "Centurion," and on the other by the Admiralty, that in realistic conditions the ships' guns would prevent bombing attacks being pressed home. Accordingly, the R.A.E. in October 1930 was given the task of developing the target. This was to be capable of being launched from ships' catapults, of simulating level and dive bombing attacks and torpedo attacks and, of alighting on the sea. Contrary to previous practice, an existing aircraft was selected, the Fairey III.F, which conferred the advantage of being able to check the functioning of most of the equipment with a pilot and observer on board. The original Pilot's Assister principles were embodied in a completely new set of automatic equipment to cope with signal initiation and transmission, reception and identification, automatic stabilisation in pitch and yaw, including the ability to perform fast and slow turns in either direction, climbing, level and diving flight and, to glide at the desirable approach angle. Three throttle positions were associated with (*a*) climb, (*b*) level, (*c*) glide and dive.

A number of safety devices were embodied to deal with emergencies. For example, if the engine speed became incompatible with the throttle setting, denoting engine failure, the aircraft would quickly adopt its landing glide condition and would turn continuously in one direction until, at 1,000 feet, it would fly straight and land. Again, the aircraft would pull out from a dive attack at 1,500 feet and automatically start to climb. As a further example, if the radio link failed for more than a few minutes, the aircraft would also glide down and land.

One free gyroscope was designed to control the aeroplane through operation of the rudder and elevator. No aileron control was provided but the dihedral of each wing was increased by 5° to give enhanced stability in roll. Automatic thermostatic control of the radiator shutters was provided. Furthermore, the landing manoeuvre was designed to be entirely automatic and to occur in response to the trailing aerial weight hitting the sea. It was arranged that the landing glide should be set so that sudden application of full elevator would just destroy the vertical velocity of the aircraft.

It is of considerable interest that the automatic landings of the Fairey Queen and the Queen Bee, which will be described later, and automatic normal take-off from land, which became the usual practice with the Queen Bee, did not suffer through the omission of aileron control.

As in other contemporary British automatic pilots, longitudinal control of the aircraft was obtained through the elevator by means of an accelerometer monitored gyroscope. With this device, the tendency was to put the nose of the aircraft down in response to longitudinal acceleration. To reduce this effect, unwanted during all pitch transitions, the motion of the throttle was caused to bring into operation a compensating torque during the time the throttle was moving. To introduce the same compensation during launch, it was decided to launch the aircraft in the "level" attitude and automatically to operate the "climb" signal when the aircraft left the launching trolley, thus causing the throttle to open. This mechanism appeared to be justified by mathematical prediction of the manoeuvre. After preliminary flying during the autumn of 1931, with a crew on board, the aircraft was taken to Lee-on-Solent in January 1932 and floats were fitted. After some flight tests, the aircraft was mounted on the catapult of H.M.S. *Valiant* on 21st January (Fig. 8). Persistent bad weather prevented the launch of the aircraft until 30th January and even then in a wind which was variable in both speed and direction. When launched, the aircraft had little excess lift as it appeared to gain only about six feet in height in the first two seconds. The aerial was released and the throttle opened to the climb position. However, the aircraft gradually lost height until, about 18 seconds after the launch, it struck the sea. The behaviour of the aircraft indicated that the means, previously described, for counteracting the effect of the acceleration on the gyroscope were insufficient and subsequent investigations revealed that the theoretical prediction of the motion of the aircraft had been too optimistic. It was therefore decided to apply appropriate modifications and to try again.

The next flight took place on 19th April 1932. After launch, the aircraft started gaining height immediately but the right wing dropped quickly and the aircraft yawed to the right at an increasing rate. After 18 seconds, the aircraft started losing height rapidly and 25 seconds after launch it dived into the sea nearly vertically. It was concluded that the failure was probably due to the inability of the rudder control to check quickly the disturbance subsequent to the launch. The rudder was extremely heavy; furthermore, wind tunnel tests confirmed that the poor lateral control of the seaplane was due to deficiency in the weathercock stability as compared with the landplane. To cope with both these deficiencies, it was decided to design and fit a more powerful and aerodynamically balanced rudder for the next trial.

In the light of the previous two failures, primarily due to catapulting, in view of the fact that many successful flights under complete radio control had been made by the aircraft when flown to a suitable height by a human pilot, and in the face of political pressure to ensure that the sole remaining aircraft could be used as a target, the Air Ministry suggested to the Admiralty that the third aircraft be flown to a safe height by a human pilot who would descend by parachute, leaving the aircraft as a wireless controlled target for gunnery trials. Accordingly, preparations were made to fit a ladder to assist the pilot to get out of the aircraft. The pilot who was originally selected, F./Lt. J. A. T. Ryde, was injured as the result of a practice parachute jump at Henlow. Another pilot was chosen as a substitute and made some tests in the Aldershot Command Swimming Baths, to find out whether or not it was possible for the parachutist to swim clear should he be enveloped by the parachute and to investigate the functioning of the quick release gear under these conditions.

Eventually, technical buoyancy prevailed, and it was decided in August 1932 that the aircraft should be catapulted after all but that no gunnery trials would take place on this occasion. The third pilotless flight took place on 14th September 1932. The aircraft behaved satisfactorily at launch and after it was clear that it was settled in a straight climb, the first radio signal "fast right turn" was transmitted and received correctly.

It had been previously decided that the purpose of this flight was to test the launch and the landing and that the flight should be as short as possible. The reliability in flight under radio control had been tested for many hours at Farnborough and Lee-on-Solent with a pilot aboard, and the decision to curtail the flight was further justified by an apparent unreliability of the ship's radio transmitter. Accordingly, after nine minutes flight, the aircraft was landed in a somewhat rough sea. Although the landing was heavier than was expected, only slight damage was caused to the propeller and undercarriage struts.

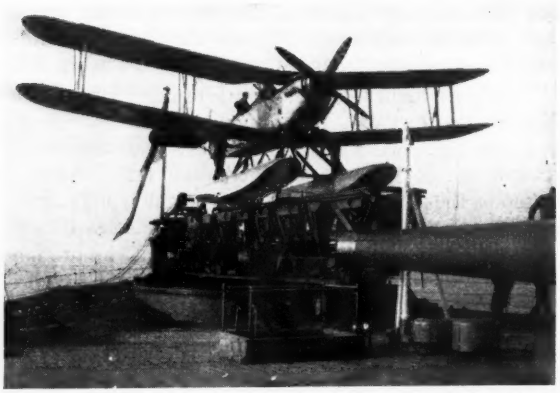

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FIGURE 8. The Fairey Queen.

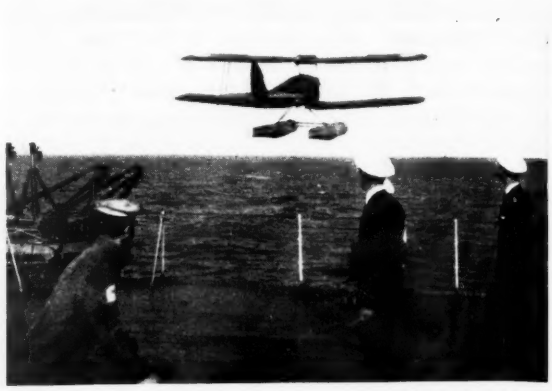

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FIGURE 9. A Queen Bee launch.

FAIREY QUEEN—FIRST GUNNERY EXERCISE, GIBRALTAR, JANUARY 1933

The single remaining aircraft was taken to Gibraltar to give the Home Fleet, during its Spring cruise, the opportunity to have a realistic anti-aircraft gunnery exercise. In the event, this proved to be a remarkably dramatic and exciting culmination of this phase of target aircraft development and, indeed, it proved to be a landmark in the history of British Naval anti-aircraft gunnery. The preparations for the exercise were not without incident but eventually the R.A.E. "circus", as they were named by the ship's company, went on board H.M.S. *Valiant* and the aircraft was mounted on the ship's catapult. It had been prescribed that great care should be taken not to lose the aircraft, except due to gunfire and, when the appointed day of the exercise dawned, the Commander-in-Chief was faced with a dilemma, as a decidedly fresh wind was blowing and the sea was too rough, in the opinion of the Fleet aviation experts, to permit the III.F. to survive a landing. The C.-in-C. decided to take the risk as he thought it improbable that the aircraft would be required to land. The whole of the Home Fleet, including H.M.S. *Nelson* and H.M.S. *Rodney* made an impressive sight as the ships steamed south to Tetuan Bay where the exercise was planned to take place. The aircraft was launched and climbed to height successfully and very few eyes in the Home Fleet did not watch the first shell bursts. It soon became clear, however, that previous opinions of lethal distance were wildly wrong and the aircraft continued to fly unmolested by a steadily increasing intensity of gunfire. After nearly two hours all ammunition had been used and the aircraft was throttled back and manoeuvred in preparation for landing. At this stage, the Commander-in-Chief was reputed to have instructed the preparation, although not the transmission, of a signal to the effect that H.M.S. *Valiant* should not delay to collect the wreckage as he was anxious to get under way to Gibraltar. The gloomy predictions of the Fleet's aviation experts had not taken into account the fact that the Fairey III.F. was designed to make its landing at the minimum possible speed, while most pilots landed at a somewhat higher speed. The aircraft flattened out just below the crests of the waves and after ploughing through the tops of a few of these, it subsided, apparently undamaged. The aircraft was remounted on the catapult when it was found that one undercarriage strut was slightly bent and that there was no damage due to gunfire.

The next morning, the Commander-in-Chief stated, in somewhat graphic terms, that he had witnessed a miracle the day before. He was convinced of the need for more target exercise of this kind in order to improve gunnery, of the ability of the Fairey Queen to land in such a rough sea and finally, of the excellent qualities of the R.A.F. powerboat, which was the most popular small boat attached to the Fleet at that time and was in great demand.

A post-mortem was held shortly afterwards in London, when it was decided that the target should be taken to Malta in order that the Mediterranean Fleet, some of whose ships had done very well in gunnery classifications exercises, should have the opportunity to engage the target. This exercise took place in May 1933, between Malta and Sicily. Owing to some engine defect, it was found impossible to climb the aircraft above 8,000 feet and after about 20 minutes engagement at this height, when the aircraft was simulating level bombing attacks, H.M.S. *Shropshire* succeeded in shooting it down. It was clear from the beginning of the exercise that *Shropshire*'s gunnery was of a high standard and this result provided well-needed encouragement to the Naval gunners. The Commander-in-Chief, Mediterranean Fleet, Admiral Cunningham, was also most impressed by the potentialities of the target and the powerboat.

Queen Bee

After the successful Fairey Queen flight in September 1932, it was decided not to engineer the Fairey Queen target and its equipment for production but to develop as quickly as possible a less ambitious target aeroplane which would be easier to handle in the Service and would be much cheaper. It was decided again to choose an existing aeroplane which could be

flown by a pilot and after considerable discussion with de Havillands, a hybrid type was selected. This was virtually a Tiger Moth (D.H.82) except for the fuselage, which was of the wooden D.H.60 type. The aeroplane had to be modified to be suitable for catapulting and receiving a float undercarriage which had to be specially designed and many other special features were included, such as provision for towing and slinging on a crane and for mounting the many items of special equipment. A contract was placed with the firm in February 1933 and the first man-plane version of the aeroplane was delivered to the R.A.E. within two months. Concurrently, the radio and automatic pilot equipment were substantially re-designed with the aim of simplification and reliability. Except that only one rate of turn was catered for, all other manoeuvres and emergency precautions were similar to those provided in the Fairey Queen.

The first attempt at a pilotless flight was made nearly a year after the inception of the project and was a qualified success. The experiment took place in the English Channel from H.M.S. *Orion* (Fig. 9). The aeroplane was successfully launched from the ship's catapult and various manoeuvres were satisfactorily executed until, when the aircraft was flying at low height in a slow right turn and gradually losing height, it was found impossible to get any response to further signals. The aircraft continued to fly in a wide circle and at one critical point appeared to be about to crash into the bridge of the ship. The Chief of the Air Staff and many other senior officials were on the bridge and tension built up rapidly. The Control Officer continued to press buttons, most of the Naval officers who were in familiar surroundings ran for cover, an R.A.E. official laughed hysterically, and the Chief of the Air Staff stood his ground and slowly turned up the collar of his greatcoat. The tension relaxed when the aeroplane just missed the ship and eventually crashed into the sea a short distance away. Tape records of the transmission showed that when the trouble began, the ship's transmitter had started to send a continuous signal and continued to do so until the end. This was subsequently found to be due to a key which had become stuck in the main transmitter circuit. While disappointing, it was satisfactory to know that the launching trouble which had bedevilled the earlier Fairey Queen attempts, had again been successfully overcome and, in view of the exhaustive and successful flying under radio and automatic control which had been done with a safety pilot on board, considerable confidence in the future of the project resulted from this trial. (Fig. 10)

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FIGURE 10. A pilotless Queen Bee alighting.

As time went on, more and more aircraft were provisioned and additional features introduced. The most important of these was the conversion to complete land operation when it was arranged that control could be exercised either from land or ship or a shepherd aeroplane, and readily handed over from one to another. Normal take-off from the ground was successfully developed, thereby obviating the need for floats or catapulting. When the aircraft was returned to base by its shepherd after an exercise, control was handed over to the base station and with the aid of very simple sighting arrangements, it was found possible to manoeuvre the aircraft into a suitable landing glide. Thereafter the entire landing operation was completely automatic as in previous landings at sea. Other features were the provision of navigation lights which could be switched on or off at will by radio in order to simplify the operation of the target at night and, if necessary, to make the target less difficult for the gunners. Eventually a Queen Bee base was established at Manorbier and five permanent Queen Bee units were established round the coasts of Britain. These bases were principally for Army exercises while the Navy conducted exercises in the West Indies, at Malta, Alexandria, Singapore and Hong Kong. Altogether, 420 Queen Bees were built and many of these survived 20 or more gunnery exercises.

The Queen Bee enjoyed the distinction of being the first-in-the-world anti-aircraft target of a realistic kind to be used extensively in operations and there is no doubt that gunnery techniques greatly improved as the result of the many exercises against these targets.

There are many stories relating to the behaviour and misbehaviour of the Queen Bee. On one occasion, the Commanding Officer at Manorbier was rung up by a colleague who commanded a station in Cornwall with the announcement that one of his Queen Bees had appeared and made a good landing in the immediate neighbourhood of the Cornish airfield. On another occasion, the aircraft was lost to sight in cloud during exercises in the Mediterranean and, due to a rapid deterioration in the weather, was not subsequently brought under control. Those in charge of the aircraft's operation omitted to switch off the ship's transmitter which, by continuing automatically to repeat at regular intervals the last signal, prevented the Queen Bee from landing in response to the built-in-radio failure emergency scheme and instead it continued to fly on a straight course until fuel was exhausted. An estimate was made of the point at which the aeroplane should have come down and a destroyer was despatched to try to find it. After steaming 70 nautical miles, the aeroplane was found intact, floating gently on the swell.

On a much later occasion, in fact early in the last

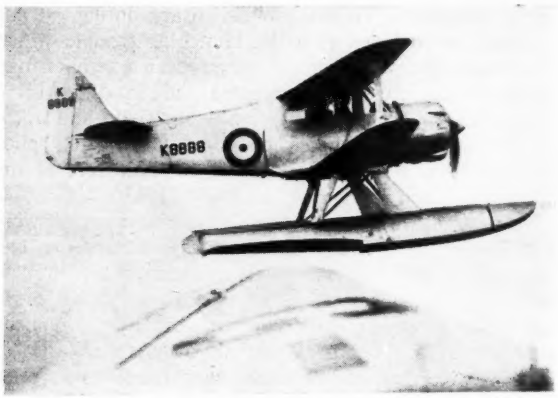

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FIGURE 11. The Queen Wasp.

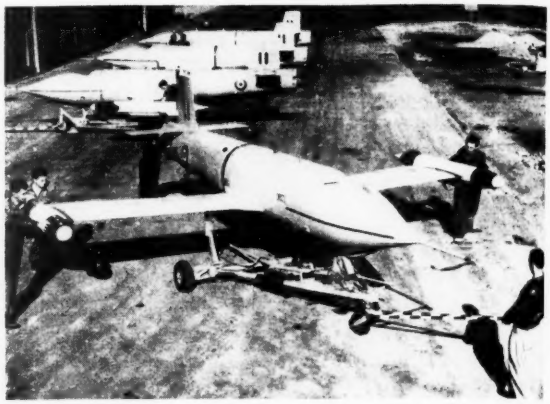

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FIGURE 12. The Jindivik.

War, when uncontrolled rocket projectiles were being tested at Aberporth, two Queen Bees were adjusted to dive very steeply in order that the rocket projectiles could be tested against such a target. The target, on its first diving attack on the site, was directed into wind with the result that it attacked from near vertical, much to the embarrassment of the many interested high officials who were present to witness the exercise. The Queen Bee survived the first dive, pulled out automatically at a very low height and was manoeuvred into a second dive during which some damage was inflicted which caused the aircraft to go out of control. Miraculously, however, it landed practically undamaged in a nearby cornfield.

Development of Target Aircraft Subsequent to Queen Bee

The extensive use of the Queen Bee which continued until late in the last War established the great value of pilotless aeroplanes as targets and the requirement inevitably arose for a higher performance target. A special man-carrying aircraft was developed by the Airspeed Company (Queen Wasp) but when development was well advanced and production was contemplated, Lord Beaverbrook, then the Minister of Aircraft Production, cancelled the project as a small contribution to his drive for greater production of manned fighter aircraft (Fig. 11). Later during the War, a Martinet was converted to pilotless operation (Queen Martinet) with a view to providing a higher performance target but production was not authorised. Later still a Spitfire was converted for pilotless operation but none was provisioned for Service use.

JINDIVIK

The next real stimulus to the development of target aeroplanes came with the advent of the guided missile. It was suggested to the Australian authorities in 1947 that they should undertake the development of a high performance target aeroplane which would be required later as a target for surface-to-air and air-to-air guided missiles at Woomera. The performance suggested was 500 knots at 50,000 feet. The Australian authorities quickly agreed to undertake this task providing the engine, automatic pilot and radio gear were supplied by U.K. (Fig. 12). The work done by Mr. Ian Fleming and his colleagues in the Government Aircraft Factory in tackling this difficult objective is noteworthy and the success achieved by this team in collaboration with the staff of the Weapons Research Establishment in South Australia, particularly in mastering the acute problem of landing the aeroplane, is worthy of the highest commendation.

Jindivik targets of the performance stated are now made available on the Woomera range for guided missile exercises as a matter of routine and the rate of loss, excluding those aircraft damaged by guided missiles, was last year one in 18 flights, a remarkable figure. The first three Jindiviks were each arranged to carry a pilot but subsequent production aircraft were built as pilotless aircraft from the outset.

Subsequent to the initiation of the Jindiviks, work was put in hand in the U.K. to develop Fireflys and Meteors for pilotless operation. Both now take off when required from R.A.E. Llanbedr for engagement by guided missiles launched from R.A.E. Aberporth and target Meteors are now provided as a service at Woomera. Canberras are also being developed by Short Bros. and Harland Ltd. for use as target aircraft for guided missiles, but are not yet in use.

Further Automatic Pilot Developments

AILERON CONTROL

Although the R.A.E.'s Pilot's Assister was entirely satisfactory as an automatic means of flying the aeroplane, the demand for accurate bombing gave rise to the need to stabilise aircraft more precisely as sighting platforms. At this time, indeed until the introduction during the war of the R.A.E. Mk. 14 Bombsight, most bombing was done with the aid of a pre-set vector bombsight which could give accurate results only in the absence of bank. It was customary, therefore, during bombing runs to make course corrections by means of flat turns. Accordingly, an ingenious additional gyroscopic unit was designed to define the vertical, both

in straight and turning flight, and to constrain the aeroplane to fly unbanked in relation to this vertical. (Fig. 13).

If the rotor axis is not level, the weight applies a torque to the outer ring. This causes a precession of the inner ring about the vertical axis. The resulting displacement of the valve causes the servomotor to apply a torque to the outer ring which counters the torque applied by the weight and prevents further azimuthal precession of the gyroscope. The opening of the valve, however, lifts one or other of two light spring arms from an adjustable stop and so causes a slight torque about the vertical axis. This torque precesses the gyroscope slowly about the outer gimbal axis until this ring lies in the vertical plane when the weight ceases to operate.

The somewhat complex sequence of these operations is required to ensure that the gravitational control will operate accurately during a turn as well as in straight flight. During a turn the centripetal acceleration of the weight causes the gyroscope to precess in azimuth at the same rate as the aeroplane is turning. Thus, providing the outer ring is vertical, there will be no movement of the valve and its associated spring and the lateral level of the gyroscope will not be disturbed. If, however, the gyroscope is not level, it will subside to the level position during a turn in exactly the same way as during straight flight.

This nice arrangement whereby the displacement of the apparent vertical during a turn does not displace the lateral level of the gyroscope, depends upon a predetermined relationship between the speed of the aeroplane and the speed of the rotor, for the former controls the centripetal acceleration and the latter the gyroscopic reaction against which it is balanced. The system is tuned by adjustment of the vertical distance of the weight to suit the operating speed of the aeroplane in which the control is to be installed.

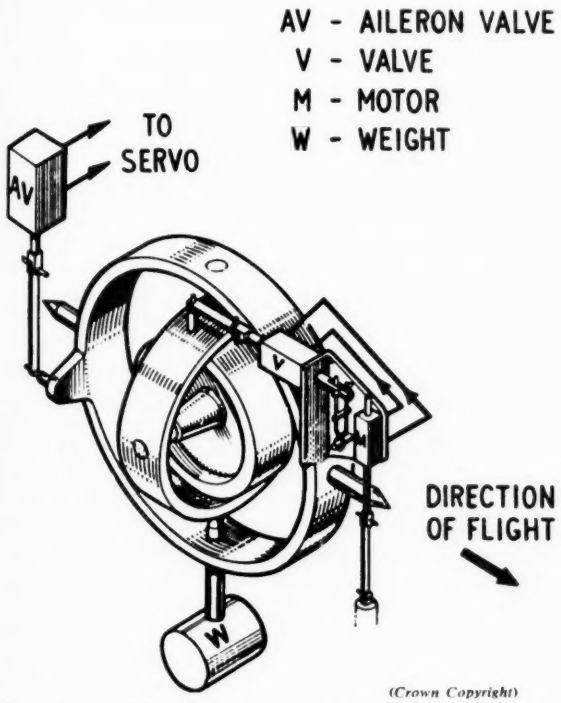

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FIGURE 13. R.A.E. Mk. 1 automatic aileron control gyroscope.

This, together with the rudder and elevator control already described, comprised the R.A.E. Mk. 1 Automatic Pilot which was widely fitted in British civil and military aircraft. Smith's Aircraft Instruments, Ltd. obtained the commercial rights of manufacture of this pilot and it was fitted to many military and some civil foreign aircraft.

In addition to the main features of the evolution of this automatic pilot which have been described, much theoretical and experimental work was done to improve the accuracy and reliability of the automatic pilot. For example, in 1926, H. M. Garner (now Sir Harry Garner) investigated theoretically the effects of time lag in the application of rudder during automatic flight. He drew attention to the destabilising effect of lag on the quick period oscillatory motions which, in the absence of control, were inherently heavily damped. This, together with contemporary experimental work, prompted substantial improvements in servomotor technique.

During the ensuing years, the great value of this automatic pilot was proved on many occasions. Its superior capability, as compared with the human pilot, of flying through extremely rough weather was most marked. Unprecedented results obtained during a large-scale aerial survey of Trans-Jordan by a Wapiti fitted with the Mk. 1 Automatic Pilot demonstrated its value for another important purpose.

MK. 4 AUTOMATIC PILOT

During the 1930's the Air Staff decided that contemporary day bombers should be fitted with automatic pilots and the requirement arose for an automatic pilot to be designed to fit into a fully equipped Hart, the standard day bomber of the time. Accordingly, the more fundamental Mk. 1 principles were embodied in a completely new engineering design which was substantially lighter than the Mk. 1 and capable of being installed in a much more confined space (Figs. 14 and 15). Eventually, owing to the wartime demand, the Mk. 4 was produced in very large numbers and fitted in many types of aircraft, including the heaviest R.A.F. bombers.

MK. 7 AUTOMATIC PILOT

The introduction of the Whitley revealed, however, that the era of flat turn bombing was over. This aeroplane would not perform flat turns at a high enough rate owing to its high weathercock stability. Accordingly, automatic steering by operation of ailerons only was investigated, both theoretically and experimentally.

Also, towards the end of the pre-War period, the possibility of exercising elevator control in response only to a combination of forward speed and acceleration was fully investigated. Aileron steering was achieved by a simple adaptation of the Mk. 4 rudder and elevator unit and the combined system was named

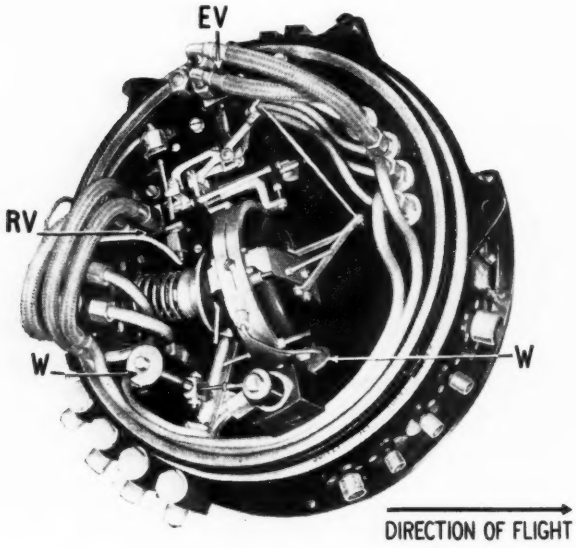

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FIGURE 14. R.A.E. Mk. 4 automatic pilot rudder and elevator gyroscope unit.

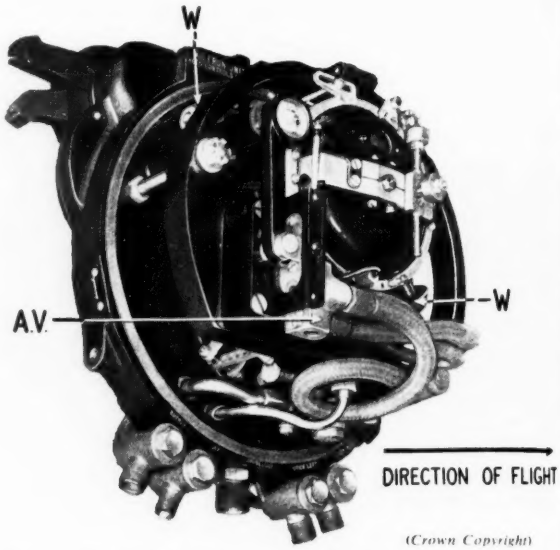

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FIGURE 15. R.A.E. Mk. 4 automatic pilot aileron gyroscope unit.

the Mk. 7 Automatic Pilot. The former pendulum-monitored pitch gimbal of the gyroscope was constrained by an anti-topple system to remain orthogonal to the outer gimbal ring and the whole unit was installed so that the gyroscope rotor axis was at 45° to the longitudinal axis of the aeroplane. The detector valve connected to the outer ring of the gyroscope which had previously caused operation of the rudder was now caused to operate the ailerons. A special, although very simple, elevator control unit was constructed to measure air speed and cause a servomotor connected to the elevator to operate in response to change and rate of change of air speed. Unfortunately, although the performance of this simple elevator control was good in average weather, it was found that in very rough air, and particularly in some heavily-laden aircraft flying at low speed, the elevator action could become dangerously violent. The lateral control part of the system proved to be entirely satisfactory, even in aircraft with a very small value of weathercock stability. The Sidestrand was typical of this class and suffered in addition from a certain amount of adverse yawing moment, due to application of aileron. In spite of these deficiencies, steering of the Sidestrand was achieved quite satisfactorily by the automatic operation of the ailerons only.

MK. 8 AUTOMATIC PILOT

It is possible that a satisfactory Mk. 7 control would have emerged if the air speed information had been caused to monitor the pitch ring of the gyroscope. But because of the wartime need for rapid production, it was decided to revert to the more familiar pendulum monitoring of the pitch ring (Fig. 16). This new automatic pilot was called the Mk. 8. It thus came about that, for the second time, the R.A.E. designed an automatic pilot based on one gyroscope which provided control about all three axes of the aeroplane. Precession of the gyroscope about the axis of the outer gimbal caused banked turns although, during a sustained turn, it was necessary for the human pilot to adjust the pitch attitude control to prevent a tendency to pitch nose-down. By this time, the R.A.E. Distant Reading Compass had become a standard fitment in all large aircraft and this was caused to monitor the course-keeping property of the automatic pilot. Another feature was the provision of automatic evasive action in the form of a continuous weave. Large-scale production of the Mk. 8 started early in 1943 and it was installed in most medium and heavy Service aircraft. It was found possible, with the effort that had been applied to the manufacture of the Mk. 4 Automatic Pilots, to produce approximately twice as many Mk. 8 pilots, owing to the simplification of the system.

Before leaving the wartime period, it is of interest to note two entirely different examples of the value of the automatic pilot as experienced during the war. As soon as war broke out, reconnaissance flights of very long duration were undertaken by flying-boats in Coastal Command, many of which had not been fitted with automatic pilots, and it was frequently found that very bad landings were made on return to base after these long flights. The use of automatic pilots transformed this situation, thereby demonstrating the serious effect of fatigue on a pilot's ability to perform a precise manoeuvre. The other example relates to a special task imposed on the famous No. 617 Squadron. They were asked to establish a feint in the Pas de Calais by trying to simulate an invasion fleet of ships during the night preceding the D-Day landings. This was to be done by flying very accurately and releasing "window," according to a carefully prescribed programme. Wing Commander Cheshire, V.C., who was in command of

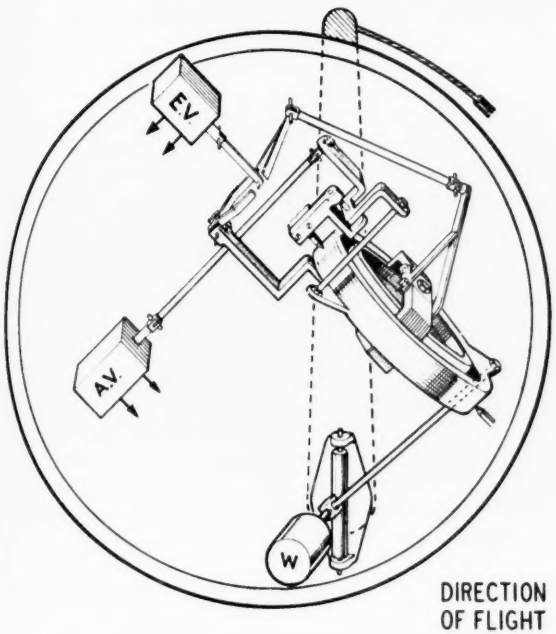

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FIGURE 16. R.A.E. Mk. 8 automatic pilot gyroscope unit.

the Squadron at this time, soon found that his Lancasters could not be flown sufficiently accurately by their crews to prevent the probable deduction by the enemy that they must be aircraft. When, however, automatic flight was tried, it was found to be entirely successful and the feint was effected with great success.

THE GONITACHOMETER AND THE MK. 9 AUTOMATIC PILOT (SMITH'S S.E.P. 1)

Meredith had left the R.A.E. in 1937 and joined Smith's Aircraft Instruments Ltd., where he continued to work on gyroscopic problems and on automatic pilots in particular. Soon after joining the firm, he invented a man-conceived version of a device embodied in flying insects. The gyroscopic mechanism of the halteres of Diptera without which they cannot sustain stable flight is fully described by J. W. S. Pringle in "Philosophical Transactions of the Royal Society" (November 1948). These halteres are vibrating pendulums which provide a gyroscopic effect. The merit of such a device as applied by Meredith lay in the avoidance of high-speed rotating machinery with its associated rubbing surfaces. Meredith designed a sensor of angular velocity on this basis which he called a Gonitachometer and which comprised a metal tine clamped at one end and maintained electro-magnetically in a state of vibration. Eventually, he built a flight model of an automatic pilot which used these sensors. It emerged, however, that substantial development would be required to make a success of this project and Meredith, in 1945, turned his attention instead to the development of what we now know as the Mk. 9 Automatic Pilot.

This was a radical departure from previous British practice in two respects. Firstly, it was all electric (a.c.) and secondly, the "rate-rate" principle was adopted whereby the angular velocities of the aircraft were detected and the control surfaces were actuated at an equivalent rate. The arguments in support of the main features of this system are very adequately presented in Meredith's lecture to the Society in 1949.[4] In the design of this automatic pilot great attention had been paid to safety and reliability. Not the least of the contributions to these was the adoption of three constrained rate measuring gyroscopes in place of free gyroscopes used formerly. One of the most interesting features in the design is the embodiment as power units of high efficiency, low inertia, hysteresis motors. By impressive development, Meredith succeeded in proving that accepted tenets of electrical engineers about hysteresis motors were wrong. It had previously been "proved" by Steinmetz that the efficiency of a hysteresis motor could not be expected to exceed a few per cent. Meredith succeeded in designing a range of hysteresis motors, varying in output power from about one watt to about 80 with efficiencies, except in the smallest size, of the order of 70 per cent. He demonstrated that when designing to a specific power, the hysteresis motor permits an economy in both the size and weight of the motor and the amplifier supplying it as compared with a squirrel-cage system.

More particularly, for military purposes, where more and more complicated tasks have to be performed, it has become essential to perform many of these automatically. The Mk. 9 and its later development, the Mk. 10 Automatic Pilot can accept, in a variety of forms, navigational guidance. A particularly alluring prospect is the achievement in service of a completely automatic approach and landing in all weather conditions. This question will be dealt with a little more fully later.

SPERRY LIGHTWEIGHT AUTOMATIC PILOT

In response to a need for a very light weight automatic pilot, the British Sperry Gyroscope Company embarked on the development of an electro-hydraulic system in the hope that it would prove possible to obtain the necessary hydraulic power from the normal aircraft supply and thereby save a substantial amount of weight. A successful automatic pilot, the Sperry Mk. 11, has been developed but, unfortunately, it was found that in the aircraft for which it was primarily intended, the hydraulic supply was unsuitable for the purpose and a separate hydraulic supply had to be provided. Some saving in weight was, however, achieved by obtaining basic attitude information from d.c. potentiometers on the normal flight instruments. The potentiometer steps are smoothed in a novel way by the use of multiple wipers with a resistance mixing network so that the resultant voltage is the mean of the individual wiper voltages. When the automatic pilot is in the pre-engagement condition, the pitch and turn controls on the pilot's controller are motored into alignment with the attitude of the aircraft so that, when the auto-pilot is engaged, the attitude at the instant of

engagement is maintained. To ensure optimum control throughout the speed range of the aircraft, the auto-pilot gearings are automatically and continuously varied with indicated air speed.

Other Aircraft Automatic Pilots

After the War, the need for a variety of auto-stabilisers and automatic pilots resulted in the development at R.A.E. and in some cases in conjunction with industry, of a number of standard components which could be used in a variety of combinations to meet the various needs. Such needs were the yaw auto-stabiliser, the automatic pilot for the Rolls-Royce "Flying Bedstead", for helicopters and for the more recent breed of target aeroplanes, particularly the Jindivik and the Meteor target. All of these auto-pilots employ a so-called "electric spring" rate gyro, originally developed in Germany (Fig. 17). In place of the mechanical spring of a conventional rate gyro the gimbal carries a d.c. potentiometer pick-off and a feed-back coil working in a powerful magnetic field, the coil being energised by the pick-off. The current through the coil, which generates a proportional restoring torque about the gimbal axis, is thus a measure of the precession rate of the gyro.

Different variants of auto-pilot equipment make use of various sensing elements such as rate gyro, vertical gyro, true air speed meter, barometric altimeter, indicated air speed meter, and in most cases the signal is picked off by a fine wire potentiometer. Such frail pick-off devices might be expected to prove unreliable, but the development of fine wire potentiometers was carried to a high standard by the Germans, possibly the most striking application being the use of this type of potentiometer to transmit information from the Patin magnetic compass. This compass, which was, of course, a vital instrument in German aircraft, operated with great reliability. The auto-pilot components employ low voltage, low impedance d.c. circuits and magnetic amplifiers. A d.c. system, while being inferior in some respects to a.c., permits processes such as integration

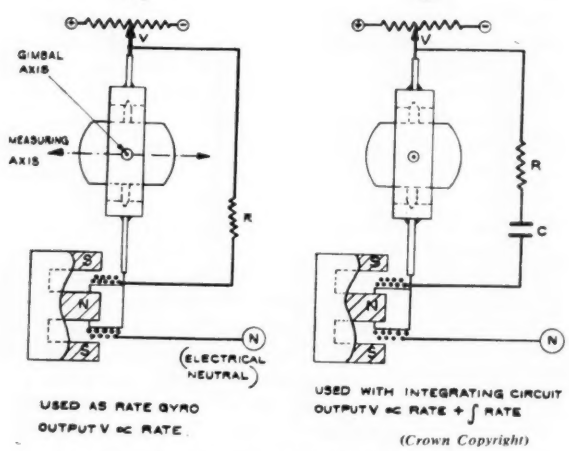

FIGURE 17. "Electric Spring" rate gyro.

and differentiation to be carried out more simply. In a number of applications the rate gyro is used with an integrating device and measures a combination of rate and integral of rate. Each servomotor is energised in an "on-off" fashion by a sensitive high speed relay, but appropriate feed-back arrangements ensure that the movement of the control surface is reasonably smooth and that the servomotor is able to sustain a steady load without jerkiness.

Variants of the Type B automatic pilot used in target aircraft permit a high degree of manoeuvrability up to 30° climb or dive and co-ordinated turns up to 60° of bank. The pitch and roll gyroscopes are mounted on separate platforms which are rotated to initiate the required manoeuvres. The Jindivik has no rudder and the Type B lateral control steers by aileron operation only. The Meteor target is also steered through the ailerons but advantage is taken of the existence of a rudder to improve control on the ground during take-off and during the approach for landing. In the Meteor target, the throttle is controlled in response to air speed.

Use of Automatic Pilots in Civil Aircraft

In British civil aircraft, the automatic pilot has been regarded as an essential operational equipment from the days of the A.W. Ensign and the Short C-class Flying Boat onwards. It was then regarded as a means of maintaining an accurate and consistent flight path and as a measure for passenger comfort and for crew comfort and efficiency; it was also then recognised that by relieving the pilot of the need to fly the aircraft manually full-time, it also enabled him to deal more efficiently with other duties; this might be regarded virtually as an important aspect of what is now known as crew fatigue policy.

The importance of the auto-pilot has increased since the earliest days of airline usage. While the original reasons for its use still apply, the auto-pilot, in conjunction with other instrumentation now provides also a means for precise maintenance of the flight altitudes and patterns required by Air Traffic Control for traffic separations in cruise and for stand-off and approach paths in regions of high traffic density. In conjunction with approach aids, it now provides the automatic approach down to the approved visibility or "ceiling" limits of altitude, with greater accuracy than is normally possible for the human pilot and, it allows the aircraft commander to concentrate more effectively on the complex procedures arising during approach in high traffic density or bad visibility conditions.

Automatic Approach and Landing

One excellent example of how the value of the modern automatic pilot, by virtue of its flexibility can be extended, lies in its contribution to the problem of automatic approach and landing.

Air transport completely independent of weather conditions has yet to be achieved on an operational basis, but automatic pilots are being used more and

more to enable aircraft to operate with regularity and safety in adverse weather. In particular, low cloud and poor visibility in the terminal area are still limiting factors but the effects of these are being reduced by the use of automatic approach. Both civil and military operators are now using auto-pilots which enable automatic approaches to be made in conjunction with the radio approach aid I.L.S. (Instrument Landing System) down to a height of about 200 feet.

The most important factor which limits the height down to which automatic approach can be used is the finite time which must be available for the visual transition and landing. This in turn is affected by aircraft approach speed, lateral manoeuvrability, downward view from the cockpit, width of runway and length and type of approach lighting pattern. One possible way of overcoming this critical problem is by extending the automatic approach technique to touchdown and possibly beyond, *i.e.* automatic landing.

The I.L.S. position information is unsuitable for landing and it is necessary therefore to provide supplementary methods to cover the landing manoeuvre from a low height on the approach to a point at which the aircraft may taxi with safety.

In one such system in course of development at R.A.E., an automatic I.L.S. approach is made to a low height when the I.L.S. inputs to the auto-pilot are switched automatically; the localiser signal is replaced by a magnetic leader cable signal and the glide path signal by a radio altimeter signal. Leader cable guidance is provided as far along the runway as necessary to cover the aircraft ground run and may be extended to cover the taxying of the aircraft. The radio altimeter information is used to reduce the rate of descent by controlling a flareout on to the runway. Control of throttle is also programmed to reduce the engine thrust on the flare and just before touch down any drift due to crosswind is automatically removed. Once on the ground, automatic control can be disengaged and the aircraft brought to rest manually. The pilot is assisted by steering instructions presented on a flight director which forms part of the fully integrated instrument and automatic control system. Numerous safety features and confidence checks have been built into the system to guard against failures and the whole operation can be monitored by the pilot on the flight director.

During the past three years, aircraft attached to the Blind Landing Experimental Unit at R.A.E. have made over 450 landings under automatic control, 400 in a Varsity and 50 in a Canberra. In some landings, manual control of throttle was exercised but in all cases all flying controls were operated automatically; 125 of the 450 landings were made during February this year without any trouble or adjustments. These landings have been supported by over 1,150 touchdowns made with only partial automatic control, for example, control in one plane only or an automatic flareout to a datum a few feet above the runway. Many of the Varsity landings have been analysed and this has shown that the mean lateral error at touchdown was 6 ft. with a standard deviation of 12 ft., the mean heading error was less than $\frac{1}{2}^\circ$ and the mean rate of descent was one f.p.s. with standard deviation of 0·8 f.p.s. The aircraft have suffered no damage in making these 1,600 partial, or completely, automatic landings. It is suggested that this is a most important and encouraging pioneering achievement.

The Modern Problem of Automatic Flight

In 1937 Meredith and Cooke and in 1949 Meredith discussed many aspects of the effect of automatic pilotage on aircraft stability characteristics. However, as the characteristics of aircraft change and as new military and civil needs emerge a re-appraisal at this stage is not out of place. Examples of these changes are the emergence of aircraft capable of flying at zero forward speed, and at the other end of the scale, at much greater speeds and heights than before.

This subject of stability and control, with particular reference to the automatic pilot has become increasingly complex throughout the years, and we are now in a régime where aeroelastic and compressibility effects are very important, where derivatives are markedly non-linear and where there are strong cross-coupling effects. However, artificial feel mechanisms and powered control systems are the order of the day and the automatic pilot designer can offer a wide variety of stiffness, damping and monitoring effects, but the satisfactory combination of all these with the aeroplane is not amenable to simple treatment. There are two broad ways in which automatic aids are used. The first is to apply them to aircraft whose handling characteristics are satisfactory without them, to perform tasks too difficult or tiresome for the human pilot. The second way, the one many people argue about, is to help the aircraft designer by the incorporation of "black boxes" in the pilot's control circuit in order to provide damping or stiffness terms which aerodynamically or by pilot's control are either impossible to provide adequately or which can be provided only at the expense of an unacceptable performance penalty.

These aids may be essential when flying at and near zero forward speed where the aerodynamicist is out of business.

The extent to which very high speed aeroplanes must have "black boxes" is more controversial; the faster we fly, the higher we ought to fly, and since aerodynamic damping falls off rapidly with height, artificial damping is more and more necessary. The extent to which artificial stiffness will be needed is more debatable and in certain cases consideration of overall aircraft performance may dominate the argument. For example, with some supersonic aircraft shapes, as the Mach number increases the fin area must be increased to retain satisfactory directional stability. A stage can be reached at which so much additional fin area is needed that further speed increase becomes impossible. At this stage the provision of the requisite directional stability by synthetic means rather than purely by areodynamics may enable speeds to be achieved which would be impossible without recourse to the "black box."

We see, therefore, that on the one hand automatic

flight near the ground and on the other hand, the dependence on the black box to provide safe handling characteristics at very low and at very high speeds, all demand absolute reliability of the automatic aids. Intensive and sustained efforts must be made by the engineers responsible for the components of the systems in order to achieve this, and thereby to earn their wholehearted acceptance by the human pilots. The black boxer who on many occasions must have seemed to be his opponent must now become the sparring partner of the human pilot and the aircraft designer.

The black box process which is happening more sedately with manned aircraft was forced from the outset in the guided weapon by the absence of the human crew, and I would like to say only a brief word about one aspect of this of some relevance to the achievement of an optimum compromise between performance and control on the one hand, and reliability on the other. The guided missile designer is deprived of the ability to test his products in many hundreds of flying hours as is the practice with manned aircraft before committing them to service. He must therefore depend greatly on theory and simulation to crystallise his design and to pursue reliability. Although there is still much scope for improvement, great success has already attended this method and I show one example to demonstrate the degree of correspondence which can be achieved between simulated and full-scale free flight. Fig. 18 relates to the behaviour of an experimental guided missile during a beam-riding flight at about twice the speed of sound. The agreement between the miss distances and between the accelerations indicates that the simulator model was indeed an adequate representation of the real situation. The investigation of which this experiment formed a part culminated in the destruction of a target aircraft by this experimental missile and if further confirmation is needed, the state of the ideal target shown in Fig. 19 which when suspended from a balloon was engaged by another

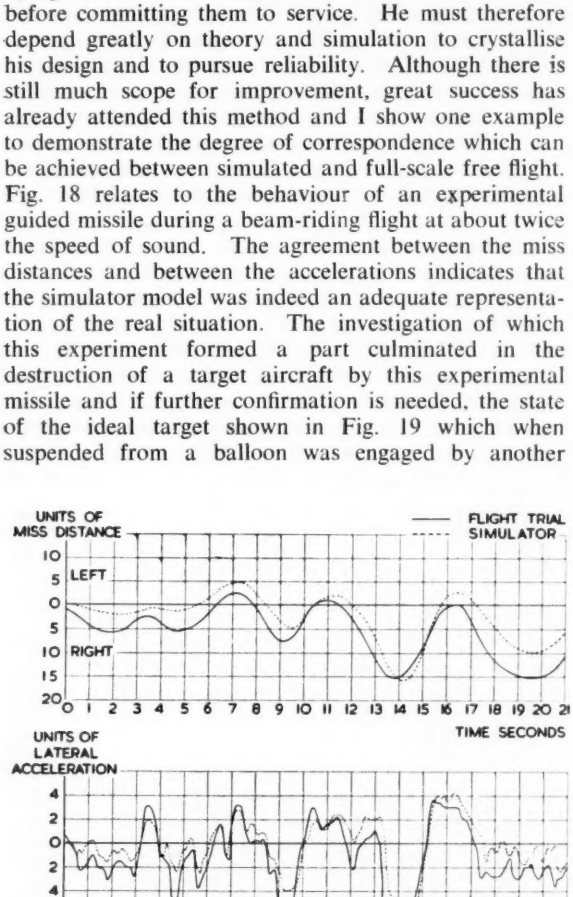

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FIGURE 18. Beam riding in the presence of radar noise and target manoeuvre. A comparison between flight trial and simulator results.

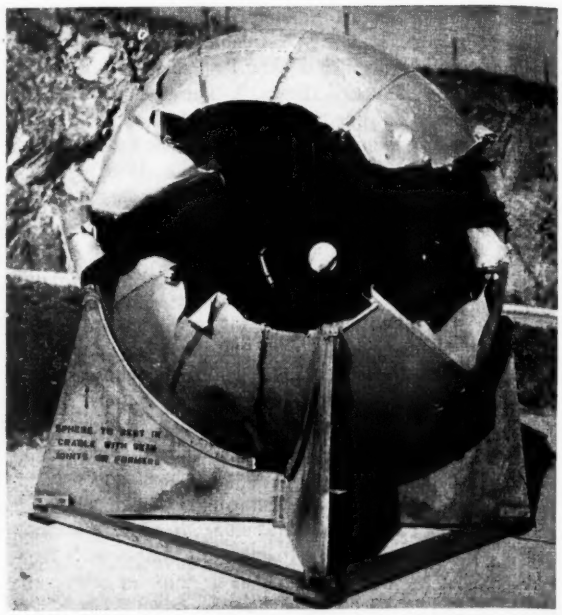

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FIGURE 19. Spherical target.

experimental missile without a warhead, speaks for itself.

There is no doubt that by extensive use of this simulator technique, much more extensive exploration can be made than would be possible in flight and thereby the best values of the various parameters can be chosen to give the degree of precision of control required.

However, it cannot be emphasised too strongly that these modern aids to simulation and computation provide a vast amount of data which is often difficult to interpret. The danger of mesmerism or laziness of mind must be constantly avoided. But, provided a problem is clearly understood and can be represented in a thoroughly representative way in such a machine, the value of the techniques as an aid to solving the problem is unquestioned.

Conclusion

We have seen in this one particular story how a military need for a missile initiated a series of developments in automatic flight in some of which we led and still lead, the world and which, in turn, provided a successful missile, a target produced in large numbers for the benefit of anti-aircraft gunnery, a series of automatic pilots capable of flying an aeroplane more precisely than could the human pilot, to the benefit of civil and military ends and, how the technique is playing its part in the modern guided weapon era. We see also the prospect of achieving automatic landings in any weather and it is hoped that our British operators will be the first in the world to adopt and demonstrate the achievement in both military and civil aircraft. There is also the possibility that more complete reliance on

automatic control may help towards manned flight of much greater performance.

Throughout the years, many have played their parts in advancing the art and it is no reflection on any of these to single out one, F. W. Meredith, for the outstanding part he played. To keep abreast in many fields of endeavour requires the sustained effort of a number of people; to gain supremacy generally requires, in addition, the inspiration of one.

This story is one of many which exemplify the part played by Government Establishments and which demonstrates the interplay of civil and military needs and benefits in the aeronautical field. By its nature, the value of the bulk of the research element of an Establishment's output is not appreciated until use is made of it at a later date in solving a problem or formulating a new requirement and, it is seldom advertised.

Many of the most important and fruitful contributions of these Establishments are in the form of new ideas and techniques, disseminated in many advisory discussions and in technical reports. Many more contributions reach the hardware stage before they are taken up by industry to engineer, produce and exploit. It is difficult to assess the extent of these contributions but it has been, and still is, formidable and has influenced greatly the tempo of the National aeronautical advance. The balance of research and development effort in the aeronautical industry and in Government establishments is of vital importance. These two efforts in guided weapons and aircraft, military and civil, are parts of one whole, they are complementary and they are inter-dependent, but this is often difficult to recognise because of the time displacement involved. The fruits of much of today's work in Establishments will be gleaned tomorrow in industry.

The most profound impact of the successful evolution of automatic flight and other allied techniques is that after a little over 50 years of manned flight in this country, the role of the strategic bomber is to pass in due course to the ballistic missile, and of the interceptor fighter to its unmanned counterpart. These decisions, together with the realisation of man-made Earth satellites, have stirred our imaginations deeply and it is of interest, in conclusion, briefly to consider the reaction of these events on future aeronautical research.

With the exception of the Wright Brothers vision we now see ahead greater scope for aeronautical research than ever before. Even though we cannot include future discoveries, as yet unsuspected, a few examples of what we know to be possible or likely to be so are sufficiently impressive. There is much to be done to achieve more fully Cayley's vision of travel by air by the ordinary man and his family; this can be done by finding out how to fly more cheaply, safely and regularly. Cheaper flight will also extend greatly the business of carrying special freight by air. Air transport at supersonic speeds will be achieved and will serve to bring cities and nations closer together. Air travel has been limited to within 10 miles or so from the Earth's surface—man-made satellites and ballistic missiles can now fly hundreds of miles above the earth; the former with virtually unlimited range. Flight between these boundaries must be explored and it will not all remain the domain solely of the unmanned vehicle which will itself succeed in escaping from the attraction of the Earth in order to explore outer space.

The growth of aeronautical research in the past half century has been an orderly progression, but the scope with which we are now faced demands the exploitation of new and often divergent scientific areas and the scale is such that the utmost discrimination must be applied to the formulation of a programme of research which will promise the best return for our limited effort.

It is believed that the combination of Industrial and Government research and development, which played its part in the Battle of Britain and in the establishment of Britain's contribution to the strategic deterrent, will be applied to a programme of work from which will emerge further great contributions to our security and prosperity and to the welfare of the common man.

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A vote of thanks to Dr. Gardner was proposed by Major G. P. Bulman, C.B.E., B.Sc., F.R.Ae.S. and seconded by Mr. A. V. Cleaver, F.R.Ae.S.

Major G. P. Bulman (*Fellow*): This Forty-Sixth Wilbur Wright Memorial Lecture would have been appreciated by Wilbur and Orville as a human tale of endeavour, failure and success; success which still went on. Those who could look back, over the past 30 or 40 years, as he could, would be particularly pleased that Dr. Gardner had referred to such men as McKinnon Wood, Cooke and Meredith.

Dr. Gardner's Lecture was a parable leading to a major moral at the end—research and the future for it and research for military and civil purposes could not be divided. Research was like the seed put into the ground and forgotten, only to appear with splendid results months, or perhaps years, later. Research over the years in the aero-engine field had permeated through all internal combustion engines. Some of it at the time was not thought to be of great importance, yet it had all contributed.

Sir Winston Churchill, in a letter published that morning about the new college to be built with his name in Cambridge wrote: "The future of Britain depends on the skill and craftsmanship with which we can meet the

challenge of the new technical age . . . We are still a great trading nation and still a great power. But it is only by leading mankind in the discovery of new worlds of science and engineering that we shall hold our position and continue to earn our livelihood."

They would inherit those new worlds of science and engineering foreshadowed by that great Englishman only to the extent of their achievements in research pure and applied, as in the past. Whether it be called military or civil was immaterial; both produced essential knowledge. Whether the work be done in Establishments or by Universities or by Industry was again beside the point. They too formed the sides of the same coin as Dr. Gardner emphasised at the end of his account of one typical form of research extending back over 30 years, yet still serving as the foundation of things to come.

It was with the greatest pleasure that he moved a formal vote of thanks to the Lecturer.

Mr. A. V. Cleaver (*Fellow*): Dr. Gardner need not have apologised for the historical character of the lecture. Many of the most urgent lessons they needed to learn were, in their most fundamental sense, historical rather than technical. Among the "interesting pointers" which had emerged from the lecture was the need for continuity and perseverance in research and development policies. They had heard how, during the First World War and in the nineteen-twenties and thirties, there was a fairly modest programme of development on what would now be called a cruise-type guided missile, or flying bomb. Although this showed every promise, it was dropped at the crucial point but a few years later a similar weapon was used by others.

Another valuable point shown by the Lecturer was the inextricable way in which military and civil developments were bound together. Many of the same techniques for the guided weapon would in due course enable civil air transport services to operate with safety in all weather conditions, day or night. They also made possible radically new types of aircraft—with jet lift or other similar devices —and finally they would be essential when rocket vehicles eventually carried men beyond the atmosphere to land on other worlds, which he thought would be done within a time interval no greater than that which separated Dr. Gardner's lecture from the Wright's first flight.

For Dr. Gardner's reference to this last sort of automatic flight—space flight—he personally was particularly grateful, but for the whole of his most illuminating discourse he had the greatest pleasure in seconding the vote of thanks.

Following the Lecture the Annual Dinner of the Council of the Society was held at 4 Hamilton Place, W.1, at which the following were present:—

Dr. A. M. Ballantyne, T.D., B.Sc., Hon.F.C.A.I., A.F.I.A.S., F.R.Ae.S., Secretary of the Royal Aeronautical Society. A. D. Baxter, M.Eng., M.I.Mech.E., F.R.Ae.S., Chief Executive of the Rocket Engine Division, de Havilland Engine Co. Ltd., Member of Council. E. C. Bowyer, C.B.E., Director, Society of British Aircraft Constructors. Major G. P. Bulman, C.B.E., B.Sc., F.R.Ae.S., Director of Construction and Research Facilities, Ministry of Supply. Member of Council and Honorary Treasurer.

Sir Sydney Camm, C.B.E., F.R.Ae.S., Past President, Director and Chief Designer, Hawker Aircraft Ltd., Gold Medallist, 1958. T. Carter, Civil Air Attaché, United States Embassy. H. T. Chapman, C.B.E., M.I.Mech.E., F.RAe.S., Managing Director, Armstrong-Siddeley Motors Ltd. A. V. Cleaver, F.R.Ae.S., Assistant Chief Engineer (Rocket Propulsion), Rolls-Royce Ltd.

Handel Davies, M.Sc., A.F.I.A.S., F.R.Ae.S., Deputy Director General, Future Systems, Ministry of Supply, Member of Council. S. D. Davies, B.Sc., F.R.Ae.S., Managing Director, Dowty Fuel Systems Ltd., British Gold Medallist, 1958. L. J. Dunnett, C.B., C.M.G., Deputy Secretary (A), Ministry of Supply.

Sir George Edwards, C.B.E., B.Sc., F.R.Ae.S., Past President, Managing Director, Aircraft Division, Vickers-Armstrongs (Aircraft) Ltd.

Sir William S. Farren, C.B., M.B.E., F.R.S., M.I.Mech.E., Hon.F.I.A.S., F.R.Ae.S., Past President, Technical Director, A. V. Roe and Co. Limited. L. G. Frise, B.Sc., A.F.I.A.S., F.R.Ae.S., Director, Special Projects, Blackburn and General Aircraft Ltd., Member of Council.

Dr. G. W. H. Gardner, C.B., C.B.E., F.R.Ae.S., 1958 Wilbur Wright Lecturer, Director, Royal Aircraft Establishment, Member of Council. H. H. Gardner, B.Sc., F.R.Ae.S., Director and Chief Engineer (Military Aircraft) Vickers-Armstrongs (Aircraft) Ltd. Sir Harry M. Garner, K.B.E., C.B., M.A., F.R.Ae.S., Member of Council.

Sir Arnold A. Hall, M.A., F.R.S., F.R.Ae.S., President of the Royal Aeronautical Society, Director, Hawker Siddeley Group Limited. Stewart Scott Hall, C.B., M.Sc., D.I.C., F.C.G.I., F.I.A.S., F.R.Ae.S., Member of Council, Scientific Adviser to the Air Ministry.

E. T. Jones, C.B., O.B.E., M.Eng., F.R.Ae.S., Past President, Deputy Controller of Overseas Affairs, Ministry of Supply.

B. P. Laight, M.Sc., A.M.I.Mech.E., F.R.Ae.S., Chief Designer, Blackburn and General Aircraft Ltd. W. H. Lindsey, M.A., M.I.Mech.E., F.R.Ae.S., Technical Director and Chief Engineer, Armstrong Siddeley Motors Ltd., British Silver Medallist, 1958.

Edwin M. Martin, Minister for Economic Affairs, United States Embassy. P. G. Masefield, M.A., Hon.F.I.A.S., F.R.Ae.S., Vice-President, Managing Director, Bristol Aircraft Limited. Colonel Ray W. McDuffee, Assistant Air Attaché, United States Embassy. M. B. Morgan, M.A., F.R.Ae.S., Deputy Director, Royal Aircraft Establishment, Member of Council.

Airey Neave, O.B.E., D.S.O., M.C., T.D., M.P., Joint Parliamentary Secretary, Ministry of Transport and Civil Aviation. W. E. Nixon, F.C.I.S., Chairman and Managing Director, de Havilland Holdings Ltd., Honorary Companion, 1958.

Colonel R. L. Preston, C.B.E., A.F.R.Ae.S., Secretary-General, The Royal Aero Club. Captain J. L. Pritchard, C.B.E., Hon.F.I.A.S., Hon.F.R.Ae.S., Secretary, Royal Aeronautical Society, 1925-1951.

N. E. Rowe, C.B.E., B.Sc., F.C.G.I., F.I.A.S., F.R.Ae.S., Past President, Technical Director, Blackburn and General Aircraft Limited.

W. F. Saxton, M.B.E., Deputy Managing Director, Armstrong Siddeley Motors Ltd., British Silver Medallist, 1958. B. S. Shenstone, M.A.Sc., F.C.A.I., A.F.I.A.S., F.R.Ae.S., Chief Engineer, British European Airways. Sir Richard V. Southwell, F.R.S., Hon.F.I.A.S., Hon.M.I.Mech.E., Hon.F.R.Ae.S., Honorary Fellow, 1958. A. Neville Spriggs, O.B.E., Managing Director, Hawker Aircraft Ltd.

W. Tye, O.B.E., B.Sc., F.R.Ae.S., Chief Technical Officer, Air Registration Board, Wakefield Gold Medallist, 1958, Member of Council.

Dr. P. B. Walker, C.B.E., M.A., F.R.Ae.S., Chief Scientific Officer, Head of Sructures Dept., Royal Aircraft Establishment, Silver Medallist, 1958. Sir Owen Wansbrough-Jones, K.B.E., C.B., Chief Scientist, Ministry of Supply. Dr. D. Williams, M.I.Mech.E., F.R.Ae.S., Deputy Chief Scientific Officer, Royal Aircraft Establishment, Bronze Medallist, 1958. L. A. Wingfield, M.C., D.F.C., A.R.Ae.S., Solicitor for the Royal Aeronautical Society.

The Application of the Theory of Stability in Structural Design

by

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The 1,058th Lecture to be given before the Society, "The Application of the Theory of Stability in Structural Design" by H. L. Cox, was given on 13th February 1958 at the Institution of Mechanical Engineers, Birdcage Walk, London, S.W.1. Sir George Edwards, President of the Society presided. Introducing the Lecturer, Sir George Edwards said that Mr. Cox had joined the staff of the National Physical Laboratory in 1926 after graduating from Cambridge. He had worked there since on problems of structural design and the structure of materials. The practical approach which Mr. Cox had to the problem was underlined by the first sentence of his conclusion—"In all questions of design it is difficult to achieve any finality."

1. Introduction—The General Theory of Design

It is never satisfactory to design a structure piecemeal. The whole construction ought to be considered as one unit and designed from the outset to meet each of the several loading actions to which it may be subjected. Part structures designed for one principal loading system and later modified to accord with other part structures or to meet other loading requirements, will seldom prove efficient. Moreover a structure designed from the outset to meet alternative loading cases is necessarily better integrated than a structure designed primarily for one loading case and later modified to meet another.

These precepts are well appreciated by designers, and they are stated here chiefly to introduce two maxims, one negative and the other positive. The negative maxim is that the strict logic of design, which clearly points the need to consider alternative loading cases simultaneously, is in this respect so utterly undeveloped that it can afford the designer no immediate help; in this respect the art of design remains a pure art.

The positive maxim is that the selection of the "best" structure for one given purpose is possible only if the characteristics of all the structures which would meet that loading case are known. In this field the logical theory of design is developed far enough to provide a sketch map. Moreover in aircraft design aerodynamic and operational requirements combine to narrow the field very markedly, so that piecemeal design of part structures soon suffices to fill in the detail of the map. Nevertheless, if attention be concentrated on too small a part of the field at one time, the map as a whole becomes ill-balanced, and the general outline of the field becomes obscured.

In respect of stability the need to maintain a wide outlook is peremptory; unfortunately the temptation to concentrate on detail is equally strong. First one has to find algebraic expressions for the critical stresses in each of several possible modes of buckling of a more or less complex structure under the prescribed loading system; then one has to invert these expressions so as to distinguish classes of structures each of which buckles under the same load; then it may be necessary to describe the behaviour after buckling in any mode which does not itself lead at once to collapse and to consider the effect of buckling in one mode on subsequent buckling in another; and finally one has to combine the conclusions regarding each possible mode of final failure in forms which will permit the designer, not merely to select the lightest possible structure, but rather to assess the weight penalty incurred by departure from the optimum in order to meet other requirements. In view of the complexity of this programme it is not surprising that the tendency has been to deal piecemeal with restricted classes of structure under the simplest possible systems of loading.

There is no doubt that this specialisation has been overdone, with the result that the detail design of this or that type of structure is far better understood than the conditions which should govern the preference for this structure rather than that. Complete redeployment of the theory in this regard is not immediately feasible, and in reviewing the present state of knowledge concentration on detail is still largely unavoidable. However, in the first approach a wider outlook will be maintained as long as possible in order to afford a glimpse of the proper division of territory between one class of structure and another.

NOTATION

E	Young's modulus
E_s	secant modulus
E_t	tangent modulus
G	shear modulus
σ	Poisson's ratio
l	length of strut or panel
b	width of plate or flange
B	width of panel or box
t	thickness of plate or flange
t_0	thickness of unstiffened plating
d or d'	depth of web of beam or box
s	thickness of web of beam or box
a	spacing of ribs or frames
A_s	area of section of stringer
$A_s k^2$	effective modulus of section of stringer
J_p	polar moment of section about its centre
h	depth of stringer web

t_s thickness of stringer web
e distance between shear centre and centre of section
P compressive load
p compressive loading per unit width of plate or flange
m bending moment per unit width of beam
f compressive stress
$f_0 = 3{\cdot}62E\,(t/b)^2$
f_c buckling stress in pure flexure or in a combined mode
f_b buckling stress in local (plate) buckling
f_t buckling stress in pure torsion
f_{opt} buckling stress for optimum beam
f_m maximum allowable stress
K buckling stress coefficient
λ half wavelength of buckle in axial direction
$\theta = (\pi d/2\lambda)$
K_1, K_2 functions of θ
$c = B/\lambda$
w weight of panel
w_0 weight of unstiffened plain plate to carry the same load as a panel
H constant (Section 2)
A, B, C, H parameters in analysis of torsional-flexural instability
μ_2, μ_3 coefficients of rotational stiffness at the edges of compressed plates
μ_T, μ_L, μ_C coefficients of rotational stiffness of a stringer.

2. Instability in Bending

If a compressive load P has to be carried over a length l the allowable stress in a tubular member cannot exceed $0{\cdot}6\,E^{\frac{1}{3}}\,(P/l^2)^{\frac{1}{3}}$; but if the compressive load is associated with an equal tensile load, parallel and not too far distant, a standard I-beam may be used; and regardless of the length of the beam the stress in the flanges is then limited only by the properties of the material. This claim is virtually true for a standard I-section; but it is not true for all I-sections.

For the moment it is convenient to disregard local and lateral instabilities of the compression flange and to deal first with the three modes in which the I-beam as a whole may fail by instability. The first is the Brazier effect, the second is wrinkling, and the third is secondary buckling of the web.

The flanges of the beam are each b wide by t thick and the web is d deep by s thick, d being measured between the mid planes of the flanges. When the mean strains in the flanges are $\pm f/E_s$, where E_s is the secant modulus, the beam is curved to a radius $(E_s d'/2f)$ and the web is subjected to a lateral compressive stress $(2f^2bt/E_s d's)$, where $1-(d'/d)=(2f^2bt/EE_s d's)$. Ignoring the moment transmitted by the web, the moment transmitted by the flanges

$$fbtd' = fbtd\,[\tfrac{1}{2} + \{\tfrac{1}{4} - 2\,(f^2/EE_s)(bt/ds)\}^{\frac{1}{2}}].$$

This is a maximum when

$$(f^2/EE_s) = \tfrac{3}{32}\,(ds/bt),$$

when also $(d'/d)=\frac{3}{4}$. Thus true Brazier instability of an I-beam occurs only after the web has compressed by one quarter of its depth. For a flat web this is of course possible only in rubber-like materials, but it could occur in a metal web if it were corrugated longitudinally.

Even when d' does not differ appreciably from d the compressive stress $(2f^2bt/E_s ds)$ may cause the web to buckle as an Euler strut, the condition governing this possibility is $(f^2/EE_s) < K\,(\pi^2/24)\,(s^3/bdt)$, where the factor K is certainly not greater than unity and may be appreciably less if the ratio b/t is high. This condition sets a fairly stringent limit on s and it will usually be the governing criterion for a flat web unless s has to be increased to meet shear requirements. However, shear requirements would be met by suitably inclining the flanges, while the lateral compression in the web could be annulled or turned to tension by curving the now tapered beam; so that in respect of loading in the sense which tends to straighten the beam neither shear requirement nor secondary instability impose any unavoidable limitation on the web. The ultimate limit is that set by wrinkling.

The condition for wrinkling with a half wavelength $(\pi d/2\theta)$ may be expressed in the form

$$(f/E)^2 = \{K_1\,(ds/bt\theta^2) + \tfrac{1}{3}\,(t/d)^2\theta^2\}\,\{K_2\,(ds/bt) + \tfrac{1}{3}\,(t/d)^2\theta^2\}$$

where $K_1 = 1/(1+\sigma)\,\{(3-\sigma)\,(T/\theta) - (1+\theta)\,(1-T^2)\}$

$K_2 = (T/\theta)/(1+\sigma)\,\{(3-\sigma) + (1+\sigma)\,(\theta/T)\,(1-T^2)\}$

$T = \tanh\theta$

and σ = Poisson's ratio (*see* Appendix I).

For low values of (d/t) the least values of f correspond to moderate values of θ and they have to be found by trial. However for values of (d/t) exceeding 80, the values of θ affording the least values of f are large and it is sufficiently accurate to take $K_1 = H\theta$ and $K_2 = H/\theta$, where $H = \{1/(1+\sigma)\,(3-\sigma)\}$. Then approximately, in the elastic range,

$$(f/E) = H\,(ds/bt)\,(1/\theta) + \tfrac{1}{3}\,(t/d)^2\theta^2,$$

and the least value is given by

$$\theta^3 = (3H/2)\,(ds/bt)\,(d/t)^2,$$

when $(f/E)^{3/2} = (3H/2)\,(s/b)$

or $(f/E) = \text{about } 0{\cdot}57\,(s/b)^{2/3}$.

In respect of an aluminium alloy box beam with $b=60$ in., $t=0{\cdot}10$ in., $d=8$ in. and $f=58{,}000$ lb./in.^{2}, the wrinkling criterion requires $s > 0{\cdot}062$ in.; but to develop 58,000 lb./in.^{2} the compression cover must be stabilised longitudinally at $2\frac{1}{2}$ in. spacing, so that this total web thickness must be divided among 25 webs each about 0·0025 in. thick. On the other hand, unless this box beam were curved to obviate cross thrust in the webs, provision against secondary instability of the flat webs would require each to have a thickness not less than 0·055 in.; and the total weight of these webs would then almost equal the weight of both flanges, whereas the basic minimum imposed by wrinkling is only about 4 per cent of that weight.

The limitation imposed on a straight beam by secondary buckling of the webs could be evaded by replacing or supplementing the webs by rows of posts; or webs about 0·0015 in. thick corrugated vertically in semi-circular corrugations about 0·25 in. in diameter might be used. However, the provision against wrinkling depends in part upon the shear stiffness of the

webs and for that reason it would probably be necessary to supplement each corrugated web by a flat web about 0·0020 in. thick; the flat webs would buckle between corrugations at about half full load, but this would not seriously impair their shear stiffness. The total weight of the webs would then be about 7 per cent of the total weight of the flanges. Well designed posts would provide the necessary stabilisation at about the same cost in weight[1].

3. The Multi-web Design as a Basic Standard

The recent rapid development of metal honeycomb cores for sandwich construction promotes multi-web construction of the type described into a practical proposal. The problems of production should indeed be rather easier than those associated with sandwich construction; the stress to which the webs are subjected is low—about 6,000 lb./in.^{2} when the flange stress is 60,000 lb./in.^{2} in the final example given above—so that a soft material would suffice; this compressive stress would press the flanges into contact with the edges of the webs, so that attachments of the flanges to the webs need be only fillet glue lines mainly to transmit shear; and in assessing the necessary strength of these attachments to cater for the effect of initial irregularities this compressive loading would provide a useful bias against the development of tensile loading across these joints.

However, the multi-web construction is here described primarily as a theoretical model which may serve as a basic standard for reassessment of the problems of wing and fuselage design. The total weight of the multi-webbed box is proportional to $2(t/d)+(s/b)$, and provision against wrinkling, including allowance for self-stabilisation of the web by corrugation, requires (s/b)=about $4(f/E)^{3/2}$, the moment transmitted per unit width $m=ftd$; therefore the total weight is proportional to $(m/Ed^2)(f/E)^{-1}+2(f/E)^{3/2}$. This weight is a minimum when $f=f_{opt}=0{\cdot}65E(m/Ed^2)^{2/5}$, when the division of weight is 60 per cent in the covers and 40 per cent in the webs. For aluminium alloy the optimum stress is attainable only when (m/Ed^2) is less than about 10^{-5}, that is when the load in the covers is less than about $100d$ (lb./in.), where d is in inches. Roughly this restricts the optimum arrangement to wings having a ratio of span to thickness less than 15. On the other hand the optimum would be attainable in a typical fuselage.

In general the weight of the multi-web beam is proportional to $(m/Ed^2)^{3/5}\{3(f_{opt}/f)+2(f/f_{opt})^{3/2}\}$ where f is the stress in the covers. In a lightly loaded deep beam the stress f_{opt} may be attainable and then the stabilising webs weigh two-thirds the weight of the covers. But in a heavily loaded shallow beam f_{opt} will exceed f_m, the maximum allowable stress in the covers; the total weight of the beam is then increased in the ratio $\frac{1}{5}\{3(f_{opt}/f_m)+2(f_m/f_{opt})^{3/2}\}$ and the ratio of the weight of the webs to that of the covers is reduced to $\frac{2}{3}(f_m/f_{opt})^{5/2}$.

When $f_{opt}>f_m$ the modulus E in the formula for f_{opt} should strictly be replaced by the reduced modulus $(E^2E_t)^{\frac{1}{3}}$, where E_t is the tangent modulus corresponding to the stress f_m. However, a significant reduction in f_{opt} due to this cause would imply other changes in the conditions which are not covered in the present discussion.

4. Webs and Stringers

For wings d is usually small and m large so that $f_{opt}=0{\cdot}65E(m/Ed^2)^{2/5}$ is unattainable. In the example above $(m/Ed^2)=7{\cdot}25\times10^{-5}$, f_{opt}=142,000 lb./in.^{2} and if f_m=58,000 lb./in.^{2}, the total weight is 57 per cent greater than the optimum while the webs weigh 7 per cent of the covers. To attain this standard with a plain sheet cover requires webs at 2½ inches spacing, but some improvement in this respect is possible by the use of stringers between webs spaced farther apart. For instance, the webs could be placed 4 inches apart with either one or two stringers spaced uniformly across the width of each plate between adjacent webs. The single stringer should be a plain rib about 0·80 in. deep by 0·10 in. thick, on plating about 0·080 in. thick; the two stringers could also be plain ribs each about 0·80 in. deep by 0·06 in. thick on plating 0·076 in thick. In either case the webs need be modified only by thickening them in proportion to the increase in their spacing. They could indeed be lightened and, if cap spars to the webs were added, the necessary web thickness would be greatly reduced (*see* Appendix I).

In designing stringers to go between webs consideration must be given to instability in torsion combined with plate buckling and to instability in flexure; the latter is governed by a formula given in Reference 3 and the condition for the former may be derived from R.Ae.S. Data Sheets in the 02.01.28 series. On the other hand these governing conditions have to be recast in special forms to permit selection of structures appropriate to the specified loading.

The three stages in this process are illustrated for the two stringer case in Figs. 1, 2 and 3 and a design diagram similar to Fig. 3 for one stringer is shown in Fig. 4. In the two stringer case the sheet cover t thick and $B(=3b)$ wide between webs is divided into three plates by two stringers each having area of section A_s and effective modulus of section A_sk^2; the buckling stress of the stiffened panel in flexure is $f_c=\frac{1}{3}Kf_0$, where $f_0=3{\cdot}62E(t/b)^2$ and the half wavelength of buckle in the axial direction B/c. In Fig. 1 by application of the Timoshenko formula contours of constant K and constant c are shown plotted on axes of $(k/t)^2$ and (A_s/bt); in addition contours are shown of $(w/w_0)=\{1+\frac{2}{3}(A_s/bt)\}^{2/3}/K^{1/3}$, that being the ratio of the weight of the stiffened panel to that of the plain plate $3b$ wide required to sustain the same load. Each point in Fig. 1 represents definite values of $(k/t)^2$, (A_s/bt) and the half wavelength of buckle (B/c); therefore the effect of shear lag on the contribution made by the sheet to the modulus of section A_sk^2 may be computed according to the form of stringer section chosen. This has been done for a plain rectangular stringer of height h and thickness $t_s=(A_s/h)$, and in

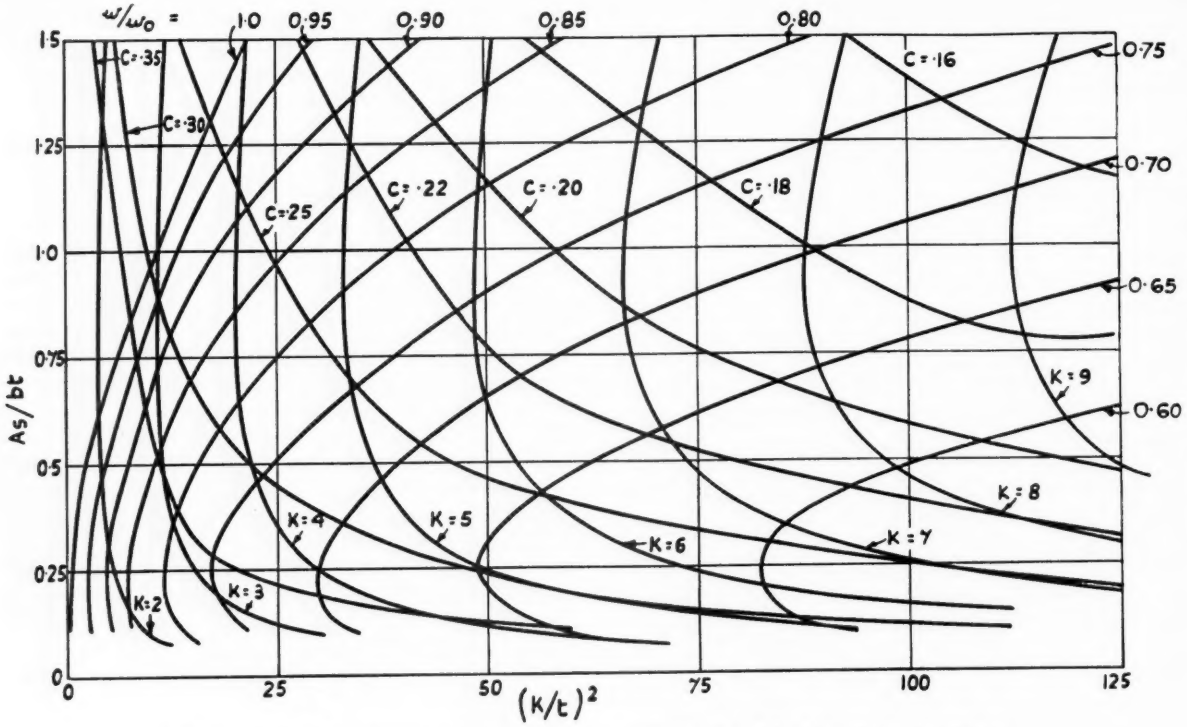

FIGURE 1. Buckling stresses, relative weights and wavelengths of buckles of panels with two stringers equally spaced between supported edges.

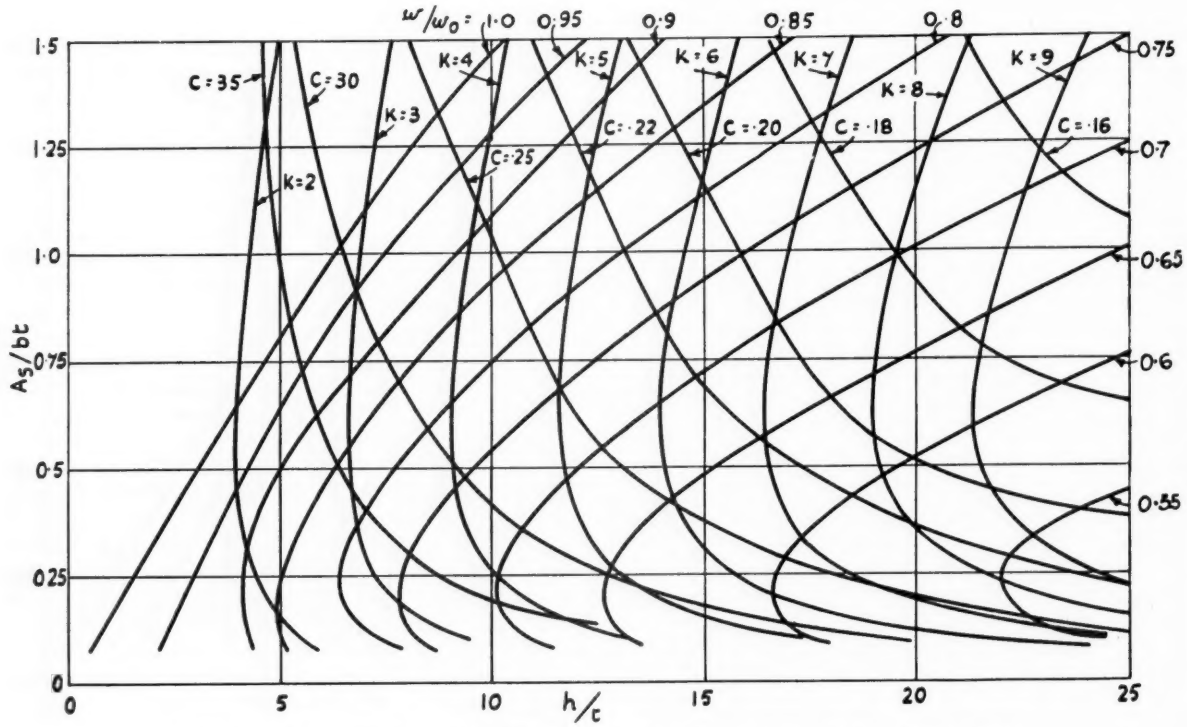

FIGURE 2. Buckling stresses, relative weights and wavelengths of buckles of two stringer panels corrected for shear lag effect.

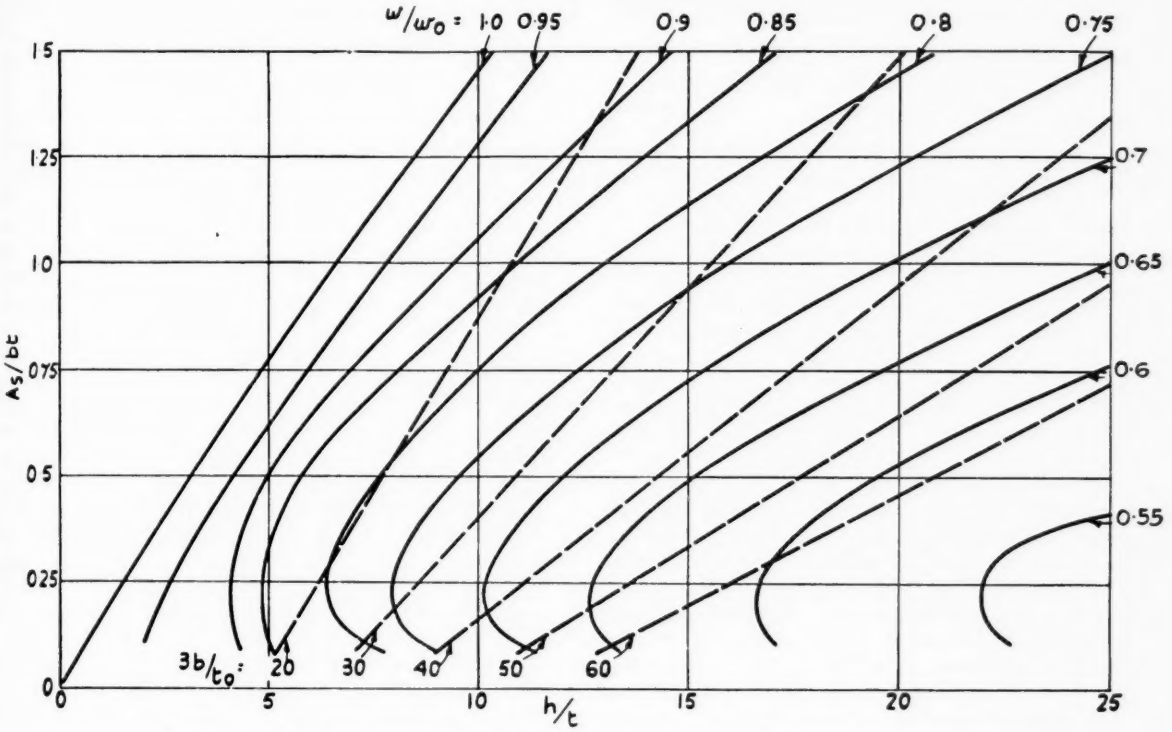

FIGURE 3. Efficiency of panels with two unflanged integral stringers in respect of flexural and local instabilities.

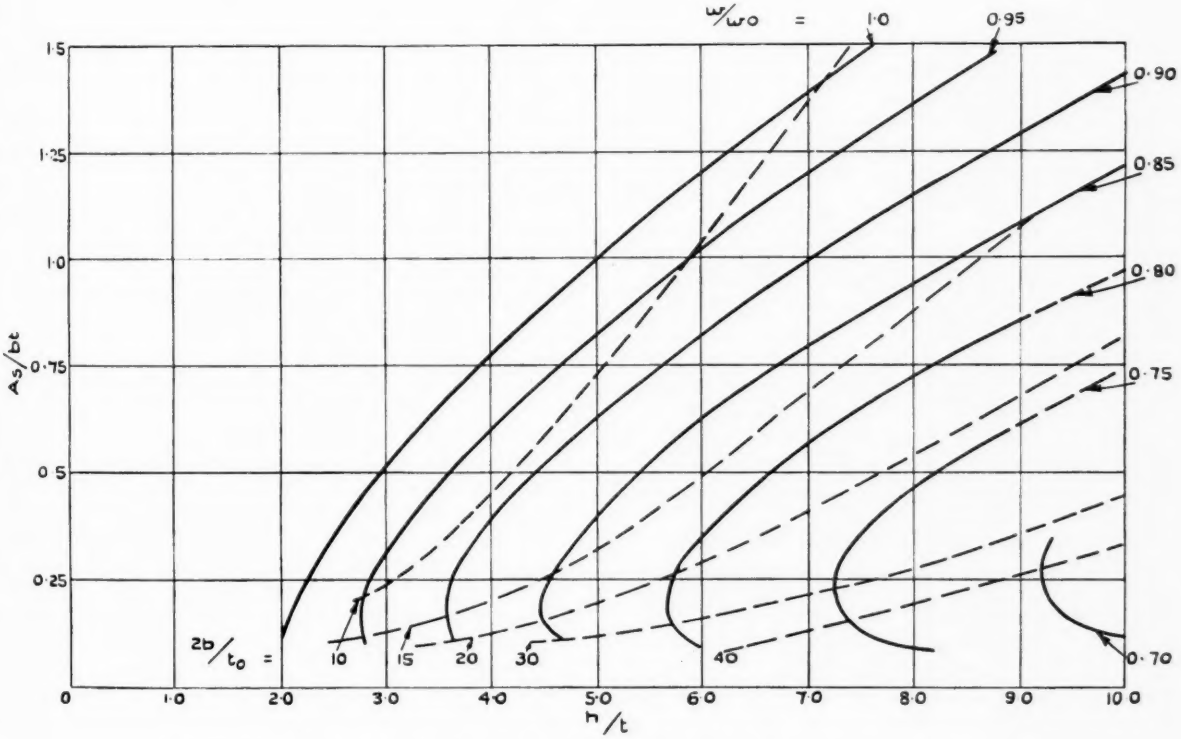

FIGURE 4. Efficiency of panels with a single unflanged integral stringer in respect of flexural and local instabilities.

Fig. 2 the basic diagram Fig. 1 has been replotted on axes of (h/t) and (A_s/bt).

If the panel is required to convey a loading p per unit width the thickness t_0 of plain plating required is given by $p=3{\cdot}62\ (Et_0^3/B^2)$. Hence $(B/t_0)=1{\cdot}54\ (p/EB)^{-\frac{1}{3}}$ and the ratio (B/t_0) may be used for convenience in place of the structure loading coefficient (p/EB); moreover for the stiffened panel

$$(b/t)=\tfrac{1}{3}\ (B/t_0)\{1+\tfrac{2}{3}\ (A_s/bt)\}/(w/w_0).$$

Then for any given value of (B/t_0) each point in Fig. 2 defines values of (b/t), (h/b) and (t_s/t), and the value of the critical stress f_b for plate buckling with stringer torsion may be computed by the use of Data Sheets 02.01.28.

Values of (f_b/f_0) were read from Fig. 2 of Reference 4 for an assumed value of (B/t_0) and a series of points on each K contour in Fig. 2. Then the value of (A_s/bt) at which $(f_b/f_0)=K/9$ indicated the point on that K contour which represented a panel liable to fail simultaneously by flexure and by local buckling at the assumed value of (B/t_0). Contours of constant (B/t_0) thus derived are shown in Figs. 3 and 4 with the contours of (w/w_0) taken from Fig. 2 and the similar diagram for the one stringer case. According to the value of (p/EB) which defines the value of (B/t_0) permissible designs are restricted to points lying above and to the left of the appropriate (B/t_0) contour. The optimum design is of course represented by the lowest value of (w/w_0) consistent with that condition; but a slight reserve is desirable in respect of interaction between the two modes of buckling.

5. Interaction between Flexural and Local (Plate) Buckling

The interaction between flexural and local buckling is purely consequential. As soon as local buckling begins the effective stiffness of the plates to axial load is reduced to about one half; in consequence if f_c is only slightly greater than f_b collapse in flexure follows almost immediately. Similarly if flexural buckling begins first the loading on the plates is increased locally and, if they were on the point of buckling before, they will at once buckle in these regions. However, local buckling which thus occurs in consequence of a buckle in flexure does not affect the structure as a whole, and collapse results only when the more heavily loaded plates become seriously over-stressed. As a rule therefore it is preferable to design the structure so that f_b is slightly greater than f_c; that is in Figs. 3 and 4 the design selected should be slightly above the appropriate (B/t_0) contour.

This type of interaction between buckling locally and in flexure is common to all structures; if f_b cannot be made greater than f_c, the value of f_c must be computed on the basis of the reduced stiffness of the plating after plate buckling. On the other hand if f_b is greater than f_c, even if the excess is small, there is no need to assess the reduction of plate stiffness before buckling due to development of initial irregularities; the change of stiffness is quite abrupt even when the irregularities are fairly great.

6. Scope for Application of Web and Stringer Designs

The examples given at the beginning of Section 4 demonstrate that for heavily loaded cases web and stringer construction offers only limited advantages. One stringer is likely to afford as great an increase of web spacing as two, and three stringers of plain rib form would almost always prove inferior. In order to use two or three stringers to advantage a form of section more efficient in bending and, more particularly, in torsion would be essential. Even then it would seldom prove possible to more than double the web spacing, and the number of webs required may still be excessive.

The more promising field for application of web and stringer construction is when the cover thickness t is limited by torsional requirements, so that only a moderate stress need be developed in bending. In the example above if t must not be less than 0·15 in. the stress in a plain sheet of this thickness is reduced to $\frac{2}{3}\times 58{,}000$ lb./in.^{2}; then the ratio h/t need not be less than 30 and the webs to stabilise this plain cover may be spaced $4\frac{1}{2}$ in. apart. Moreover by adding two stringers having $A_s/bt=0{\cdot}25$ and $h/t=10$, the average thickness of this panel is increased by one-sixth to 0·175 in. and since from Fig. 3 $(w/w_0)=0{\cdot}7$, the thickness t_0 of plain plating to carry the same load is 0·250 in., while $(B/t_0)^2=(3{\cdot}62Et_0/5{,}800)$, so that $(B/t_0)=40$. This design would have webs 10 inches apart with stringers spaced $3\frac{1}{2}$ ins. in between, each stringer being a plain rectangular rib 1·5 in. deep and 0·083 in. thick. The point $h/t=10$, $A_s/bt=0{\cdot}25$ in Fig. 3 lies well above the dotted line for $(B/t_0)=40$. Accordingly the design ought to be safe in respect of local buckling; the buckling stress for the stringer if clamped at the plates would be $1{\cdot}16\times 10^7/18^2=35{,}800$ lb./in.^{2}, in comparison with the flexural buckling stress 33,100 lb./in.^{2}; since the value of f_0 for the plates themselves is over 72,000 lb./in.^{2} this probably represents a reasonable reserve.

However, this particular example has been chosen to emphasise that the accuracy at low values of A_s/bt particularly of the dotted lines in Figs. 3 and 4 is rather uncertain. The diagrams have been prepared to illustrate the form of the relationships and to serve as a general guide; for detail design more precise computation would be needed.

7. Stringers and Ribs

If the multi-web design should prove impracticable the structure loading coefficient (m/Ed^2), that is (p/Ed), has to be discarded. The substitute immediately available is (p/EB), where B is now the width of the box between spars. The plating stiffened by stringers is then stabilised by transverse ribs supported only at the spars. The stress that can be developed in a structure of this type is $3{\cdot}38\ E(p/EB)^{0{\cdot}5}m^{-0{\cdot}3}\lambda_s^{0{\cdot}3}\lambda_r^{0{\cdot}2}$, where m is the number of stringers and λ_s and λ_r are geometrical ratios representing the flexural efficiency of the stringers and ribs[2]. For the example quoted ($p=5{,}800$ lb./in. and $B=60$ in.) typical values are $m=40$, $\lambda_s=1$ and $\lambda_r=4$, so that the stress is limited to about

45,000 lb./in.^{2}. Moreover, the weight of the ribs is two-thirds that of the plating and stringers, so that the effective stress is only 27,000 lb./in.^{2}. A third web midway between the spars would permit the stress in the plating and stringers to be increased to about 55,000 lb./in.^{2}, but the transverse ribs would still add $66\frac{2}{3}$ per cent to the total weight. In this respect the fault lies in using ribs in bending to support the stringers, rather than attaching the compression flange directly to the tension flange by members under direct stress. The long established compromise is of course to provide such support by frames spaced spanwise at a pitch less than B.

8. Stringers and Frames: Requirements for the Frames

The detail design of stringers between frames has been the subject of many investigations both theoretical and experimental, so that this part of the field of design is very completely mapped. The theoretical aspects were covered rather thoroughly in Reference 5 and the position with regard to local and flexural instabilities is well established. The position with regard to torsional instability and the interaction of torsional with other modes of buckling is not so clear. However, before turning attention to that question, it is worthwhile to notice the frames. The usual procedure has been to assume the loading p and the frame spacing a to be fixed and to assume further that the sheet cover and stringers are pinned at the frames. It has been recognised that the frames need a certain minimum stiffness[5], but no one seems to have pointed out what governs that requirement.

The governing criterion is once again wrinkling, and again secondary instability of the frames under the Brazier loads has also to be prevented. In respect of the latter the loading per unit width of the frame is rather less than $(2f^2at/E_sd)$; frames of flat plate would prove rather heavy, but there is no great difficulty in increasing the effective radius of gyration to the required extent. On the other hand if the frames alone had to provide against wrinkling of a plain sheet cover far more weight would be needed than for multi-webs; because the frames would provide little or no resistance to shear distortion in the spanwise direction so that the factor equivalent to K_2 in the formula for wrinkling in Section 2 would be very small. Wrinkling would then occur over a long wave length, probably the entire length of the beam, and the critical stress would be little more than $0{\cdot}4E\,(ts/ad)^{\frac{1}{2}}$. The derivations of the formulae for wrinkling are given in Appendix I, where comparisons are made between web and frame stabilised boxes having either plain or cellular covers.

As for webs, the requirement for the frames to prevent wrinkling is quite distinct from the requirement to prevent secondary buckling. In particular the total weight of frames required to prevent wrinkling is the same whatever their spacing, provided that the spacing is close by comparison with the wavelength of the buckled form.

9. Stringers and Frames: Design of Stringers

Since Reference 5 was published there has been continual development in stringer design. To top hats and Z's and Y's, integral construction and sandwiches with metal honeycomb or corrugated cores have since been added. The general principles can best be illustrated by reference to a form of sandwich which has not so far been used, that is a sandwich of square cells, both plates and webs being h wide and t thick; the square of the radius of gyration of this sandwich is $7h^2/36$. If this sandwich is designed to buckle at a stress f, simultaneously by local buckling and by flexural instability over a length l,

$$(f/E)=(7\pi^2/36)\,(h/l)^2=3{\cdot}62\,(t/h)^2$$
$$=(3{\cdot}62\times 7\pi^2/36)^{\frac{1}{2}}\,(t/l)=2{\cdot}635\,(t/l).$$

The loading p per unit width $=3\,ft$,

so that $(p/El)=3\,(f/E)\,(t/l)=(3/2{\cdot}635)\,(f/E)^2$,

or $$(f/E)\,(p/El)^{-\frac{1}{2}}=0{\cdot}937.$$

The optimum value for Z or Y stringers on unbuckled plating found by Farrar[5] was 0·94 to 0·95.

A slightly more general form of the plain webbed cellular sandwich would have plates b wide and t thick with webs h deep and t_s thick. For this construction, if $(b/t)=(h/t_s)=(3{\cdot}62\,E/f)^{\frac{1}{2}}$ and $b=nh$, the optimum value of $(f/E)\,(p/El)^{-\frac{1}{2}}$ is $1{\cdot}31\,\{n^2\,(1+6n^2)/(1+2n^2)^3\}^{\frac{1}{4}}$, and the maximum value is 0·941, when $n=0{\cdot}88$. However, the wavelengths of the "natural" buckles in plates and webs at $(f/E)=3{\cdot}62\,(t/b)^2=3{\cdot}62\,(t_s/h)^2$ differ in the ratio n, and in order to reconcile these to a common value the factor 3·62 should strictly be increased. By reference to R.Ae.S. Data Sheet 02.01.31, the increase is not more than one half per cent, so that the increase thus computed in the optimum value of $(f/E)\,(p/El)^{-\frac{1}{2}}$ is only two or three parts in a thousand. On the other hand, if the condition for local buckling were based in the first place on 02.01.31, the optimum value of b/h would probably prove to be slightly less and the optimum value of $(f/E)\,(p/El)^{-\frac{1}{2}}$ might be correspondingly greater.

It seems therefore that any one of several apparently quite different forms of construction, each at its respective optimum affords a value of $(f/E)\,(p/El)^{-\frac{1}{2}}$ very close to 0·95. The value found by Catchpole[4] for unflanged integral stringers was 0·81. It is not easy to distinguish the precise reason for this marked inferiority; certainly it must be attributable in some way to the inefficiency of the plain rib stringer, probably on account of its liability to torsional instability rather than its inefficiency in bending. At the same time there would appear to be equally marked differences between Z and Y stringers and the rectangular cellular structure.

Full analysis on the lines of Reference 4 for the cellular sandwich with corrugated sheet core would afford useful evidence. The optimum value of $(f/E)\,(p/El)^{-\frac{1}{2}}$ almost certainly lies between 0·81 and 0·95, probably close to the upper limit.

10. Honeycomb Sandwich Structure

Sandwich structure with a honeycomb core is in a

different class because local buckling is virtually eliminated. The core itself carries no appreciable end load and serves only to stabilise the covers against wrinkling and to afford shear connexion between them. If the core has a density ρ relative to solid metal it may be regarded as a system of closely spaced webs each web thickness being $\beta\rho$ times the spacing; the factor β represents the relative efficiency of the actual core structure under cross tension or under shear. Then in respect of wrinkling the analysis (*see* Appendix I), which leads to the formula in Section 2, needs only slight modification and it leads to two separate conditions,

$$(f/E)=\{K_1(h\beta'\rho/t\theta^2)+\tfrac{1}{3}(t/h)^2\theta^2\}$$
$$\text{or}\quad \{K_2(h\beta\rho/t)+\tfrac{1}{3}(t/h)^2\theta^2\}$$

where t is the thickness of the covers and h that of the core.

For all values of θ the second condition leads to the lower value of f, although when the wavelength is short (θ large) both tend to the same minimal value with respect to variation of θ, and that value $(f/E)=0{\cdot}57(\beta\rho)^{2/3}$ is in effect precisely the same as in Section 2. However the shear factor β is likely to be markedly less than β' so that for this reason also the resistance of the core to shear is its dominant characteristic.

The shear stiffness of the core also affects flexural buckling of the sandwich and approximately

$$(1/f)=(1/f_0)+2(t/Gh\beta\rho)$$

where f is the buckling stress,

$$(f_0/E)=(\pi^2h^2/4l^2),$$

l is the length of the sandwich panel, and $G\beta$ is the effective shear modulus of the core. The load per unit width $p=2ft$, and it is convenient also to write $r=(f/f_0)$. Then the four relations may be expressed in the forms

$$(1-r)\,\beta\rho=4(1+\sigma)(f/E)(t/h)$$
$$(p/El)=2(f/E)(t/h)(h/l)$$
$$r^{-\frac{1}{2}}(f/E)^{\frac{1}{2}}=(\pi/2)(h/l)$$
$$\text{and}\quad \beta\rho=2{\cdot}34N(f/E)^{3/2}$$

where in the last the factor $N(>1)$ represents the reserve against failure by wrinkling. Then by elimination of (t/h), (h/l) and $\beta\rho$,

$$(f/E)=\{\pi(1+\sigma)/2{\cdot}34N\}^{\frac{1}{2}}r^{\frac{1}{2}}(p/El)^{\frac{1}{2}}/(1-r)^{\frac{1}{2}}.$$

The effective stress, however, is $f_r=f/(1+\gamma)$, where

$$\gamma=(\rho h/2t)=\{2(1+\sigma)/\beta\}(f/E)/(1-r).$$

From this last relation it is clear that $1-r$ is of order f/E so that $r^{\frac{1}{2}}$ differs from unity only by this order of magnitude. Hence, ignoring the factor $r^{\frac{1}{2}}$ and eliminating $1-r$ it follows that

$$(f_r/E)=(\pi\beta/4{\cdot}68N)^{\frac{1}{2}}(p/El)^{\frac{1}{2}}\{\gamma^{\frac{1}{2}}/(1+\gamma)\}.$$

The maximum value (0·529) of the γ-factor occurs when $\gamma=\frac{1}{2}$; but the factor exceeds 0·5 for all values of γ between 0·25 and 1·00. Thus the efficiency factor takes the new form

$$(f_r/E)(p/El)^{-\frac{1}{2}}=\text{constant}.$$

For comparison with cellular and stringer stiffened structures

Farrar $F=(f_r/E)\ (p/El)^{-\frac{1}{2}}=\{\pi\beta/4{\cdot}68N\}^{\frac{1}{2}}\ (\gamma E/f)^{\frac{1}{2}}/(1+\gamma)$.

When $\gamma=0{\cdot}25$ and $f=60{,}000$ lb./in.^{2} in aluminium alloy, $F=4{\cdot}23(\beta/N)^{\frac{1}{2}}$, so that with $N=2$ the value of F will exceed the highest achievable with the older forms of construction, provided that β is not less than 0·10. The factor of reserve N on wrinkling is desirable to avoid over-stressing of the glued joints by development of initial irregularities into the wrinkled form; but the appropriate value of N can only be decided by experiment. The value of β depends on the geometry of the honeycomb, on the regularity and perfection of the honeycomb structure and on the attachment to the skins, so that for this parameter also recourse must be had to experiment. Throughout the foregoing analysis it has been tacitly assumed that the honeycomb structure is designed to afford a near approach to continuous webs without appreciable shear stiffness in the lateral plane. Of course cores are available having comparable stiffnesses to shear in all transverse planes and in narrow panels the lateral shear stiffness would endow the panel with properties approaching those of a plate of thickness h. However, in respect of efficiency the lateral stiffening is akin to stiffening by ribs (Section 7), and in very wide panels it would almost certainly be preferable to forego practically all lateral shear stiffness in order to achieve as high a value of β as possible (but *see* Discussion).

So much depends on detail design and so much more on production technique that it is difficult at the present time to assess how far sandwich structure may supersede the older forms of construction. It appears capable of competing even up to the highest values of structure loading coefficient and in the medium range it offers great advantages. Nevertheless the greatest gain is offered at low values of structure loading coefficient, when the cube root of (p/El) is much to be preferred to the square root It is curious that in this field practical development is slow.

11. Interaction between Primary Modes of Buckling

When a straight parallel structure of uniform section under uniform compression begins to buckle the distortion must always vary sinusoidally along its length. The distorted form of the cross section is therefore the same for all sections, and the buckled form of the structure is represented completely by description of the distortion of one cross section, together with statement of the half wavelength of the distortion along the length. Immediately buckling begins the stiffnesses of the several parts of the structure in other modes of deformation characterised by different wavelengths will be altered and this may either precipitate, or delay, buckling in these other modes. This kind of consequential interaction, instanced in respect of flexural and local buckling in Section 5, is strictly the only kind of interaction that demands separate consideration. However the term "interaction" is also applied to primary buckling characterised by a single value of wavelength, when that wavelength and the corresponding mode of distortion represents a compromise between conflicting tendencies in separate elements of the structure to buckle in elementary modes of different types.

The most familiar example of this kind of primary

interaction occurs in integral construction with plain unflanged stringers. These stringers are most liable to buckle by torsional instability over as long a wavelength as possible, whereas the plates between the stringers favour a half wavelength not longer than their own width. If the plates are dominant the half wavelength chosen is not much greater, but if the stringers prevail there may be only one or two half waves in the length of the test panel. The general terms of settlement of this conflict are indicated in Fig. 1 of Reference 5 or Fig. 2 of Reference 4; but the precise detail of the boundary between the two spheres of influence has yet to be agreed.

Similar problems of interaction between local buckling, preferring a short wavelength, and torsional buckling, which favours a long one, are amenable to analysis by reference to R.Ae.S. Data Sheets in the 02.01.28 series. In applying these data it is always necessary to explore all permissible wavelengths because in the disputed region the minimum critical stress abruptly shifts from short to long wavelength (or vice versa), and the minimum value in the rejected wavelength range may then be replaced by a maximum. For an ideal structure the boundary between the short and long wave regions is a line of discontinuity; the contours of constant critical stress must be continuous through the boundary line but will usually have cusps on it; the contours of constant wavelength are not continuous through the boundary and are, in effect, completely independent on either side. When local irregularities are present the transition is probably more continuous in the manner indicated by Catchpole.

In local and torsional buckling the form of distortion is virtually agreed and only the wavelength is in dispute; in this case the actual critical stress is not less than the lower of the two critical stresses for the two simple modes of buckling considered separately. On the other hand, when the wavelength is virtually agreed and the conflict is between distinct modes of distortion, the actual critical stress is usually lower than either of the critical stresses for the two separate modes. This is the case for interaction between flexural and torsional instability.

12. Description of the Buckled Form

The buckled form corresponding to any assumed wavelength may always be represented by rotation of the cross section about one or several axes parallel to the length of the structure. In pure flexure, for instance, the whole section may be considered to rotate as a whole about an infinitely remote axis in the neutral plane, whereas local buckling consists in a group of rotations about several axes.

In local buckling the positions of these axes are known and the problem for analysis is to decide the relative amplitudes and senses of these rotations consistent with the condition that the net moment about each axis of rotation must be zero. There is one such condition for each axis of rotation and all these conditions are linear and homogeneous in the amplitudes of rotation; hence elimination of the rotations would lead to a single determinant which equated to zero would define as many critical values of the compressive axial stress as there are axes of rotation. Usually however it is possible by symmetry to infer some, or all, of the relations between the amplitudes of rotation and hence, to reduce the complexity of the final formula for the critical stresses.

In some instances, such as that treated in Reference 4 torsional instability may be included in the same general scheme; in particular the axes of rotation may be pre-determined. On the other hand, when torsional instability interacts with flexural, the axes of rotation are the result of compromise between the two modes, and their positions have to be found by analysis. Interaction between flexure and torsion arises whenever the axis of rotation lies at a finite distance from the centre of section. In respect of the compact section of a free strut this results when the shear centre, the natural centre for torsion, is separated from the centre of section; in comparison with the critical stress f_t for pure torsional instability and the critical stress f_e for pure flexural, interaction results in a critical stress lower than either; if $f_t < f_e$ the axis of rotation is near the shear centre but on the farther side from the centre of section and the mode is mainly torsion; if $f_t > f_e$ the centre of rotation is much farther away and the mode is mainly flexure; if $f_t = f_e$ the actual critical stress is approximately $f_t\{1 - e(A_s/J_p)^{\frac{1}{2}}\}$ where e is the distance between the shear centre and the centre of section, A_s is the area of section and J_p is the polar moment about the centre of section.

In stringer-stiffened flat panels all centres of rotation are virtually bound to lie in the plane of the sheet, because any other centre of rotation would involve curvature of the sheet in its own plane, and this is very strongly resisted. If the principal axes of the stringer section are parallel and perpendicular to the sheet, pure flexure by rotation of the whole section of the panel about an infinitely remote axis in the plane of the sheet is still possible, although pure torsion of the stringers is not. With Z-section stringers the principal axes of the stringer section are not parallel and perpendicular to the plane of the sheet and all modes of buckling, other than purely local, necessarily involve both flexure and torsion of the stringers.

13. Method of Analysis

The method of analysis (*see* Appendix II) of torsion-bending modes follows the same general line as that used for analysis of local buckling. The positions of the centres of rotation in the plane of the sheet cover have to be treated as variable but otherwise the procedure is to equate to zero the total moment of resistance about each axis of rotation. The positive contributions to this total moment arise from pure torsion and torsion-bending of the stringer section, including the effect of simple bending arising from the offset of the centre of rotation from the shear centre; a negative contribution arises from the axial compressive stress; and contributions, which may be either positive or negative, arise from the plates on either side of each stringer.

The most interesting case is that of the panel with Z-section stringers buckling in the mode which is

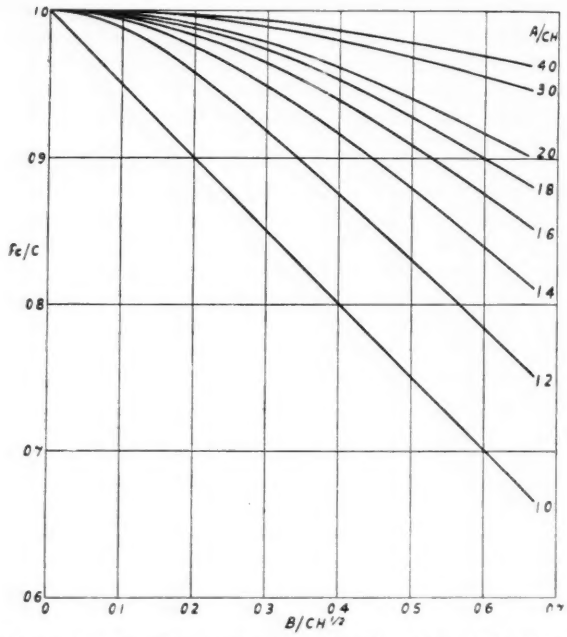

FIGURE 5. Interaction between flexural and torsional instabilities of a panel with Z section stringers.

almost pure flexure. For a wide panel the condition of support at the side edges has no important influence and it is reasonable to assume that each of the stringers in the central portion of the panel rotates about a centre equidistant from the stringer web; this common distance is large but not infinite and the stringer section rotates as it is displaced. The displacement is the same at each stringer and this displacement is communicated also to the sheet cover; as a result the axial compressive stress in the sheet cover contributes a negative term to the moment about the centre of rotation.

The effect of interaction of the torsional mode with pure flexure is represented in Fig. 5. In this diagram C is the critical stress for flexural buckling as ordinarily computed from the apparent section modulus of the complete panel. A/H is the critical stress for torsion of the stringers combined with plate buckling; since the stringers twist all in the same sense, the appropriate stiffness coefficient for the plates is μ_3 from R.Ae.S. Data Sheet 02.01.33, and it is immaterial that the plates are also translated because the pure moments about the plate edges may equally be assumed to act about the true centres of rotation. $B/CH^{\frac{1}{2}}$ is the coefficient of interaction which is proportional to the cross modulus I_{yz} of the stringer Z-section.

This diagram, Fig. 5, which relates to the case when the critical stress for pure torsion A/H is greater than that C for pure flexure, is applicable also when $C > A/H$, merely by interchanging A/H with C, so that the ordinates become values of $f_c/(A/H)$, the abscissae values of $BH^{\frac{1}{2}}/A$, and the curved lines of constant CH/A. However, under these conditions the

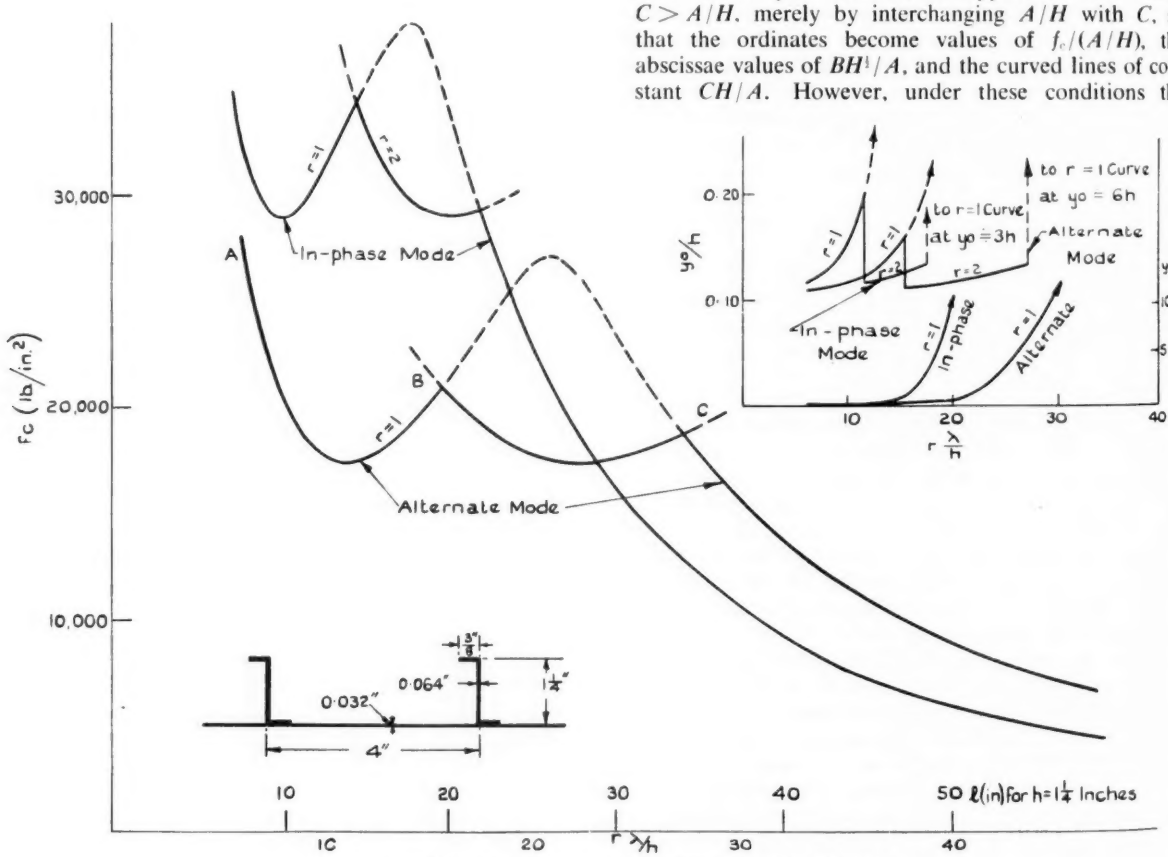

FIGURE 6. Buckling stresses for a fuselage structure with a thin skin.

mode of buckling would be mainly torsion by rotation about axes close to the feet of the stringer webs, and this mode with the stringers rotating all in the same sense will almost certainly yield a higher critical stress than the mode in which alternate stringers rotate in opposite senses; because in the latter case the appropriate stiffness coefficient for the plates is μ_2 from R.Ae.S. Data Sheet 02.01.31, which is likely to be much less than μ_3. Even in the alternate mode, flexure of the stringers still interacts and reduces the critical stress below the value for pure torsional instability; Fig. 5 still applies, but since the wavelength is short the corresponding value of C is high, so that CH/A is large and the effect is slight.

Complete analysis leads to diagrams of buckling stress against length of panel, like those shown in Figs. 6 and 7. Each of the two main curves has a minimum value at a fairly short panel length, then rises to a maximum and finally falls steadily as the panel length increases. In the regions of the first minima the centres of rotation lie close to the feet of the stringer webs, but as the maximum values are approached the centres of rotation move rapidly away and are in fact well removed before the continuously falling portions of the curves are reached; because in the region under the maxima of the main curves the first minima are repeated with two half waves in the panel length; and in consequence the centres of rotation are at first confined to regions very close to the feet of the stringer webs and then suddenly remove to distances equal to one or two plate widths.

In these examples the mode of buckling of a long panel is mainly flexural with some torsion and the stringers rotate all in the same sense (in-phase mode), but at a panel length of about 25 inches in Fig. 6 and about 28 inches in Fig. 7, the alternate mode with adjacent stringers twisting in opposite senses in two half waves supervenes. In this respect, however, the diagrams probably underestimate the critical stresses for buckling in the alternate mode. In computing the curves full allowance was made for the reduced axial stiffness of the plates already buckled between the stringers, but no allowance was made for the effect of the corrugations formed in the buckled plates in increasing their contribution to rotational stiffness about the lines of attachment to the stringers. This effect is certainly not negligible, but there is no established method to compute it.

14. Interaction Between Torsional and Local Instabilities

The stress systems associated with torsion-bending modes are all virtually constant through the thickness of the wall of each component flat, whereas the stress systems associated with local buckling are pure bending and torsion of the flats. Accordingly there can be no interaction between these internal stress systems. On the other hand there is interaction in respect of the negative contributions to torsional stiffness which arise from the axial

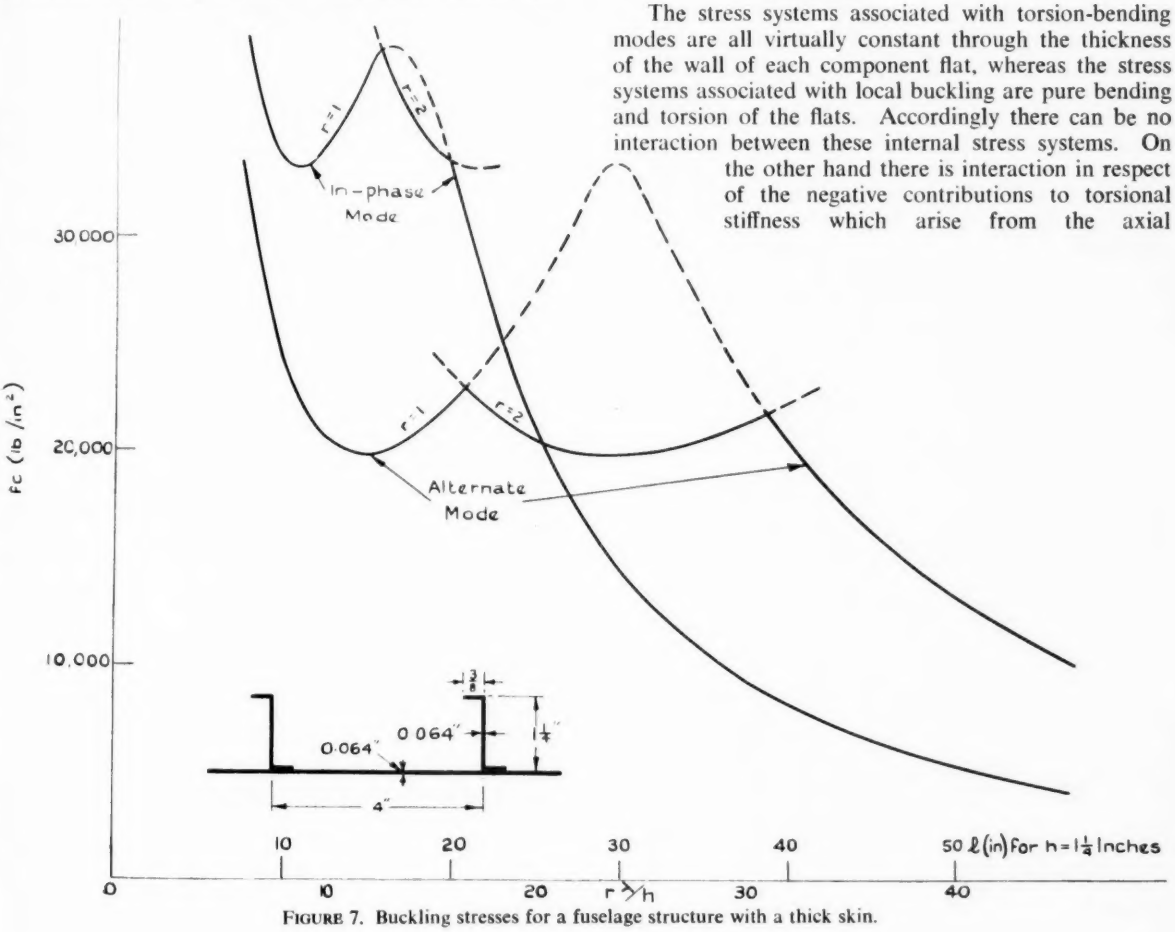

FIGURE 7. Buckling stresses for a fuselage structure with a thick skin.

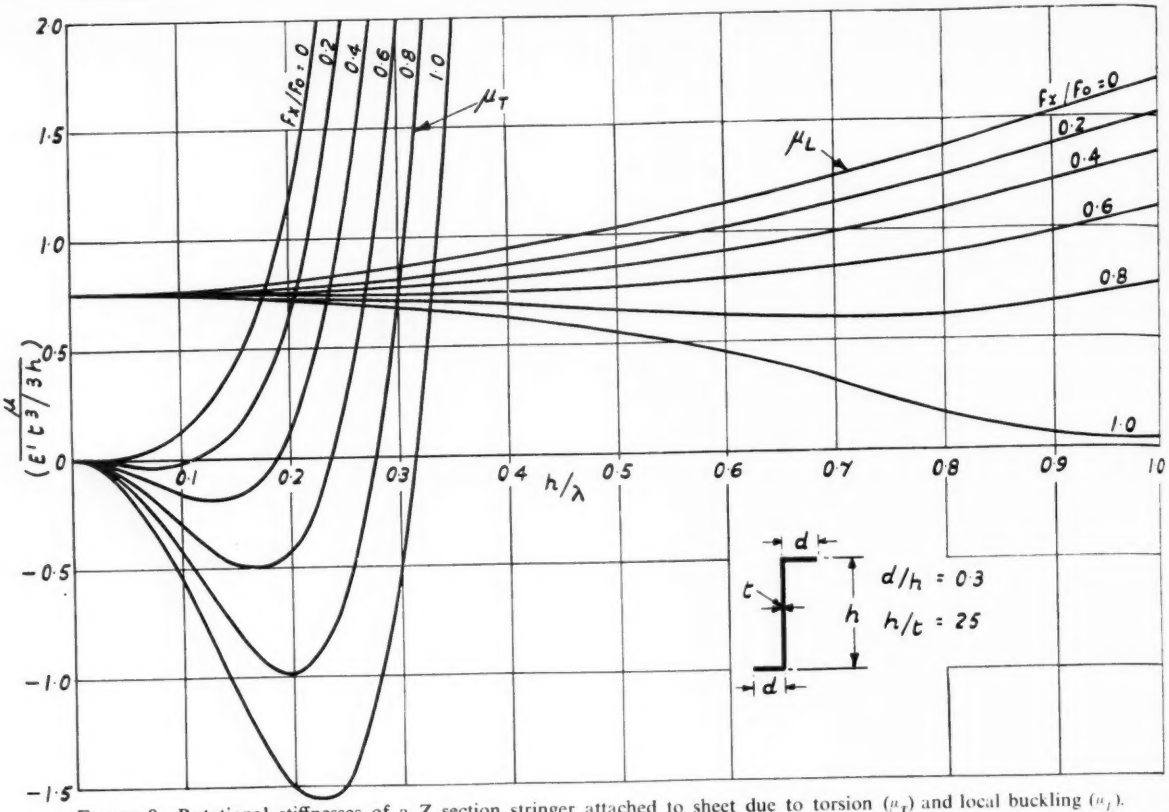

FIGURE 8. Rotational stiffnesses of a Z section stringer attached to sheet due to torsion (μ_T) and local buckling (μ_L).

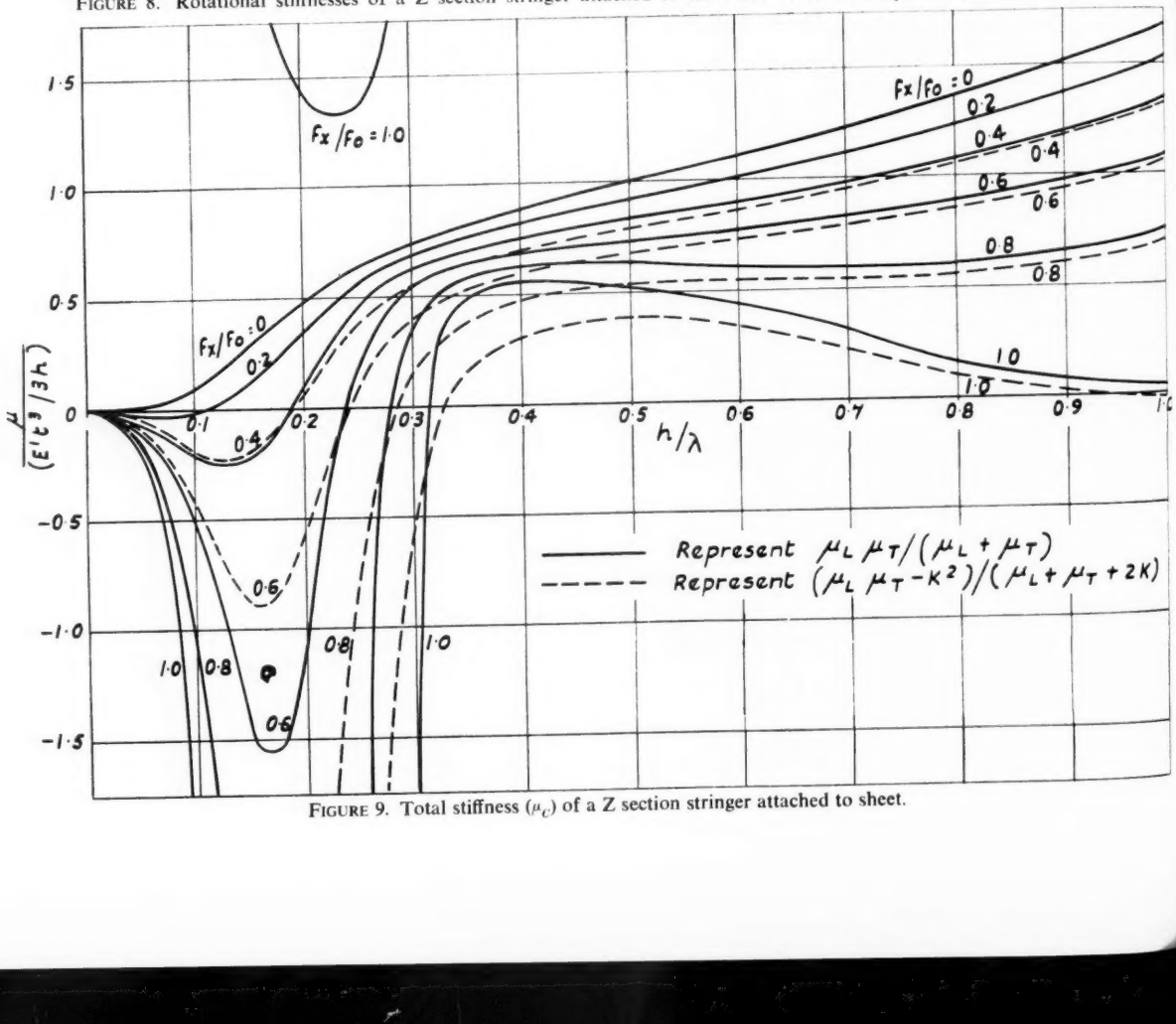

FIGURE 9. Total stiffness (μ_C) of a Z section stringer attached to sheet.

compressive stress, because the translations of parts of the cross section resulting from local buckling modify the contribution to torsional stiffness arising from the rotation of the undistorted cross section.

The result of an approximate allowance (*see* Appendix II) for this type of interaction is illustrated in Figs. 8 and 9 . Fig. 8 shows the variation with wavelength and axial compressive stress of the pure torsional stiffness μ_T of a typical Z-section twisted about the foot of its web and of the similar torsional stiffness μ_L associated with local buckling; Fig. 9 shows values of μ_C the result of combining these two stiffnesses, the full lines representing the harmonic mean between μ_T and μ_L with no allowance for interaction and the dotted lines representing the corrected values of μ_C when interaction is taken into account. The difference is not marked except in one or two regions near maxima or minima.

15. Wrinkling

Another important type of interaction is that between flexural and local, which results in wrinkling. If the stringers are integral with the plating, or very firmly attached, rotation of the stringers all in the same sense results in no greater displacement of the sheet cover as a whole than the displacement of the stringer webs; and the negative contribution arising from the axial load in the plating is balanced by the flexural stiffness of the stringers. The negative term varies inversely as the square of the wavelength, while the positive one varies inversely as the fourth power; accordingly the type of instability that affords the lowest critical stress is flexural-torsional over a long wave length.

On the other hand, if the stringers are attached only by rivets, rotation of all the stringers in the same sense about points close to the feet of the stringer webs on the side remote from the rivets results in greater displacement at the rivet lines than at the stringer webs. The average displacement of the sheet cover outward from the stringers may then be as great as that at the rivet line, and the negative contribution to the moment about the axis of rotation is increased relative to the positive contribution from the flexural stiffness of the stringers. Over a long wavelength this effect slightly increases the liability to torsional instability in the in-phase mode and may reduce the critical stress for this mode below the value for the alternate mode, particularly as the contribution from the plates to the positive moment about the centre of rotation (the μ_3 term) may be appreciably reduced by local deformation of the attached flange of the stringer.

The more important effect is, however, in respect of buckling over a half wavelength comparable with the depth of the stringer web, because due to local buckling the effective contribution of the stringer to the restoring moment may then be very small, or even negative, while the restoring moment due to the plates (the μ_3 term) is also much less. Since the wavelength is short several half waves must develop down the length of the stringers and it is necessary to consider not only the half waves in the outward sense, where the sheet cover separates from the stringer flange, but also the adjacent half waves in the inward sense, where the sheet cover tends to push into the stringer webs. Displacement of the sheet cover in this sense cannot of course develop far before meeting strong resistance from the stringer webs; but with usual types of formed stringer section there is enough slack to allow the movement to begin. Once this form of flexural-local buckling has begun the loads set up in the rivets and the attached flanges of the stringers rapidly increase to values sufficient to fracture either the rivets or the stringer flanges, and a complete wrinkle develops across the entire width of the panel. This type of wrinkling depends primarily on the distance between the rivet line and the foot of the stringer web and the critical stress for wrinkling may be materially increased by reducing this distance. A complete method for assessing liability to wrinkling is given in References 7 and 8, based on experimental determination for N.A.C.A. countersunk rivets of the effective offset in relation to the distance between the rivet line and the stringer web and to the pitch of the rivets.

It is interesting to notice that the data given in Fig. 6 of Ref. 8 show the critical stress for wrinkling to vary in inverse proportion to the two-thirds power of the stiffener spacing just as in Section 2 (Fig. 10).

Glued-on stringers ought, of course, by theory, to be much better than riveted ones, but experimental evidence indicates less improvement than would be expected. Like all wrinkling cases the actual occurrence depends critically on the initial irregularities, and of course glued stringers would sooner yield to stresses

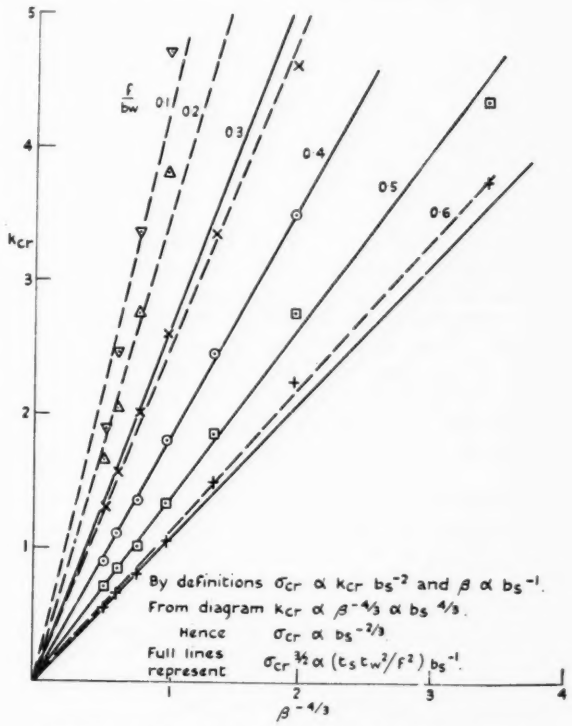

FIGURE 10. Re-plot of Fig. 6 of N.A.C.A. Report 1255.

resulting from development of initial irregularities than would rivets.

16. Conclusion

In all questions of design it is difficult to achieve any finality. Having specified the chief loading case and examined several classes of structure which meet the requirements, it still remains possible that some quite different class of structure may be at least equal to the best so far distinguished. Moreover there is no certainty that in specifying the chief loading case the practical question may not have been prejudiced by too facile reference to secondary requirements. For instance, in the reference to torsional stiffness requirement for a wing in Section 4, no mention was made of plating with waffle type integral stiffening[9], which certainly affords high stiffness in shear with little or no loss of efficiency under compression.

The line of approach adopted in the present survey has been based on the observation that in aircraft design compressive loading arises mainly in bending distributions and that the tension flange is not far distant from the compression one. On that basis it has been possible to decide the relative merits of several classes of structure according to the value of the basic structure loading coefficient (p/Ed), where p is the load per unit width in the flange and d is the depth between flanges. If (p/Ed) is large the least weight is determined almost entirely by the strength of the material and only a few per cent extra weight is needed for secondary structure to stabilise the compression flange. As (p/Ed) is reduced the optimum stress in the covers is also reduced and the relative weight of stabilising structure is increased until for values of (p/Ed) below a definite limit, the optimum structure is stressed within the elastic range and 40 per cent of the total weight may be needed to stabilise the flanges.

At low values of (p/Ed) there may be little to choose between structures of quite different types, but it appears that the optimum structures may all have at least 20 per cent of their total weight in the stabilising structure.

At high or moderate values of (p/Ed) the least total weight is achieved by the most direct attachment between the two flanges either by webs, posts or frames. When frames are used at spacing l with stringer-stiffened sheet or cellular sandwich covers, any design of stringer which is not specially liable to torsional instability affords practically the same optimum weight in relation to the value of (p/El); but honeycomb sandwich structure ought to be lighter, particularly for low values of (p/El).

In stringer-stiffened construction interaction with the torsional buckling mode may appreciably reduce the critical stress in the mainly flexural mode, and interaction of flexural with local buckling may lead to failure by wrinkling.

Perhaps the most interesting conclusions from this survey are that the true optimum stress is not excessive even for the highest value of (p/Ed) likely to be demanded, and that the weight penalty incurred by achieving only half the optimum stress may be no more than 35 per cent, because achievement of the optimum stress would demand much greater weight in the stabilising structure.

APPENDIX I

REQUIREMENTS FOR WEBS OR FRAMES IN RESPECT OF STABILISATION OF THE COMPRESSION FLANGE OF A PARALLEL BOX STRUCTURE

The box of depth d is symmetrical about its mid plane; the mean thickness of each cover is t and its radius of gyration about its own neutral axis is k. Axes Ox and Oy are taken along the length and down the depth of the box. Webs of mean effective thickness s_W are spaced b apart across the width of the box, and frames of mean effective thickness s_F are spaced a apart along its length. The bending moment carried by the webs themselves is disregarded.

When the box is subjected to a bending moment ftd per unit width, and the stresses in the covers are $\pm f$, the compression cover is assumed to undergo an additional deflection $v_c = (\lambda/\pi)(U+V)\sin(\pi x/\lambda)$ in the direction Oy, and the tension cover is assumed to undergo an additional deflection $v_t = (\lambda/\pi)(U-V)\sin(\pi x/\lambda)$ in the same sense. The half-wavelength λ is assumed to be small by comparison with the length of the box, and where necessary the frame spacing a is assumed to be small by comparison with λ. The state of limiting stability is defined by the condition that the total energy shall be invariant with respect to variation of the parameters U and V which represent amplitude of buckle.

The energy of flexure of the covers per unit length and per unit width is

$$\frac{1}{\lambda}\int_0^{\lambda}\frac{1}{2}Ek^2t\left(\frac{\pi}{\lambda}\right)^2\{(U+V)^2+(U-V)^2\}\sin^2\left(\frac{\pi x}{\lambda}\right)dx = \frac{1}{2}Et\left(\frac{\pi k}{\lambda}\right)^2(U^2+V^2)$$

The (geometrical) tensile strain of the covers is

$$\frac{1}{\lambda}\int_0^{\lambda}\left\{1+\left(\frac{dv}{dx}\right)^2\right\}^{\frac{1}{2}}dx-1=\frac{1}{4}(U\pm V)^2$$

The energy of direct stresses in the covers per unit length and per unit width is then

$$\frac{1}{2}Et\left\{\frac{f}{E}-\frac{1}{4}(U+V)^2\right\}^2+\frac{1}{2}Et\left\{\frac{f}{E}+\frac{1}{4}(U-V)^2\right\}^2$$

or $Et(f/E)^2 - ftUV +$ terms in U^4, and so on.

The energy of deformation of the frames per unit length and width of the box is

$$\frac{1}{2}E\frac{ds_F}{a}\frac{1}{\lambda}\int_0^{\lambda}\left(\frac{\lambda}{\pi d}\right)^2(2V)^2\sin^2\left(\frac{\pi x}{\lambda}\right)dx = E\left(\frac{ds_F}{a}\right)\left(\frac{\lambda}{\pi d}\right)^2V^2$$

For equilibrium of the webs in the symmetrical mode (V component) the lateral displacement must be represented in the form

$$v=\left\{A\sinh\left(\frac{\pi y}{\lambda}\right)+B\left(\frac{\pi y}{\lambda}\right)\cosh\left(\frac{\pi y}{\lambda}\right)\right\}\sin\left(\frac{\pi x}{\lambda}\right)$$

TABLE I

f for wrinkling	*Frame Bracing* $(2sk^2/adt)^{\frac{1}{2}}$	*Web Bracing* $3H^{\frac{1}{2}}(ks/bt)^{\frac{1}{2}}$
1. *Flat Sheet Covers* $\left(k^2=\frac{1}{12}t^2\right)$	$(st/6ad)^{\frac{1}{2}}$	$(3H/2)^{\frac{1}{2}}(s/b)^{\frac{1}{2}}$
Weight	$\frac{2t}{d}+\frac{s}{a}=2mf^{-1}+6m^{-1}f^3$	$\frac{2t}{d}+\frac{s}{b}=2mf^{-1}+2{\cdot}34f^{3/2}$*
	$=4{\cdot}62m^{\frac{1}{4}}\left\{\frac{3}{4}\left(\frac{f_0}{f}\right)+\frac{1}{4}\left(\frac{f}{f_0}\right)^3\right\}$	$=4{\cdot}18m^{3/5}\left\{\frac{3}{5}\left(\frac{f_0}{f}\right)+\frac{2}{5}\left(\frac{f}{f_0}\right)^{3/2}\right\}$
	where $f_0=0{\cdot}58m^{\frac{1}{2}}$	where $f_0=0{\cdot}80m^{2/5}$
When $m=7{\cdot}25\times10^{-5}$ and $E=10\times10^6$ lb./in.^{2}	$f_0(\times E)=49{,}000$ lb./in.^{2}	$f_0(\times E)=176{,}000$ lb./in.^{2}
Least Weight	$4{\cdot}62m^{\frac{1}{4}}=0{\cdot}0393$	$4{\cdot}18m^{3/5}=0{\cdot}0137$
Optimum Dimensions	$t=0{\cdot}118$ in., $a=1{\cdot}53$ in.	$t=0{\cdot}033$ in., $b=0{\cdot}47$ in.
	$s=0{\cdot}015$ in.	$s=0{\cdot}0026$ in.
		If $f_m=60{,}000$ lb./in.^{2}
		weight $=0{\cdot}0252$.
		$t=0{\cdot}097$ in., $b=2{\cdot}38$ in.
		$s=0{\cdot}0026$ in.
		(s independent of f_m)
Effective Stress	$\frac{1}{4}\times49{,}000=37{,}000$ lb./in.^{2}	$\frac{60{,}000}{1+0{\cdot}045}=57{,}500$ lb./in.^{2}
2. *Square Cellular covers* (h thick)		
$k^2=\frac{7}{36}h^2$ and $f=3{\cdot}62\,(t/3h)^2$, so that $(k/t)^2=0{\cdot}078f^{-1}$	$\frac{s}{a}=\frac{dt^2}{2tk^2}f^2=6{\cdot}4m^{-1}f^4$	$\frac{s}{b}=0{\cdot}676f^{3/2}$, $\frac{t}{k}=2{\cdot}42f^2$
Weight	$\frac{2t}{d}+\frac{s}{a}=2mf^{-1}+6{\cdot}4m^{-1}f^4$	$\frac{2t}{d}+\frac{s}{b}=2mf^{-1}+2{\cdot}42f^2$
	$=4{\cdot}16m^{3/5}\left\{\frac{4}{5}\left(\frac{f_0}{f}\right)+\frac{1}{5}\left(\frac{f}{f_0}\right)^4\right\}$	$=4{\cdot}03m^{\frac{1}{2}}\left\{\frac{2}{3}\left(\frac{f_0}{f}\right)+\frac{1}{3}\left(\frac{f}{f_0}\right)^2\right\}$
	where $f_0=0{\cdot}6m^{2/5}$	where $f_0=0{\cdot}74m^{\frac{1}{2}}$
When $m=7{\cdot}25\times10^{-5}$ and $E=10\times10^6$ lb./in.^{2}	$f_0(\times E)=132{,}000$ lb./in.^{2}	$f_0(\times E)=310{,}000$ lb./in.^{2}
If $f_m=60{,}000$ lb./in.^{2}, weight	$0{\cdot}0242\times(1+0{\cdot}0048)$	$0{\cdot}0242\times(1+0{\cdot}0036)$
Optimum dimensions	$(1/3)t=0{\cdot}032$ in., $h=0{\cdot}784$ in.	$(1/3)t$ and h the same, b limited by conditions discussed in Section 4:
	$a=14$ in. $s=0{\cdot}0016$ in.	$s/b=0{\cdot}9\times10^{-3}$

*The allowance made in Section 3 for self-stabilisation of the ultra-thin webs is omitted here, because a similar allowance ought also to be applied to the thin frames.

with related forms for the longitudinal displacement and the direct and shear stresses. At the edges of the webs

$$\left\{A\sinh\left(\frac{\pi d}{2\lambda}\right)+B\left(\frac{\pi d}{2\lambda}\right)\cosh\left(\frac{\pi d}{2\lambda}\right)\right\}=V,$$

and the ratio A/B is determined by the relation between shear loading and longitudinal displacement along these edges. The relationships in respect of the antisymmetrical mode (U component) are similar with cosh and sinh interchanged.

The energy of deformation of the webs per unit length and width of the box may then be expressed in the form

$$\frac{1}{2}E\frac{ds_W}{b}\left\{K_1\left(\frac{V}{\theta}\right)^2+K_2U^2\right\},\ \text{where}\ \theta=\left(\frac{\pi d}{2\lambda}\right),$$

and the forms stated for the parameters K_1 and K_2 in Section 2 relate to the condition when longitudinal displacement at the edges of the webs is completely prevented. (The effect of variation from this condition is only slight.)

The total energy associated with the U, V displacements is then the product of Et with

$$\frac{1}{2}\left(\frac{2k}{d}\right)^2\theta^2(U^2+V^2)-\left(\frac{f}{E}\right)UV+\frac{1}{4}\frac{ds_F}{at}\left(\frac{V}{\theta}\right)^2+$$
$$+\frac{1}{2}K_1\frac{ds_W}{bt}\left(\frac{V}{\theta}\right)^2+\frac{1}{2}K_2\frac{ds_W}{bt}U^2$$

and the condition for instability is

$$\left(\frac{f}{E}\right)^2=\left\{K_1\frac{ds_W}{bt\theta^2}+\frac{1}{2}\frac{ds_F}{at\theta^2}+\left(\frac{2k}{d}\right)^2\theta^2\right\}\times$$
$$\times\left\{K_2\frac{ds_W}{bt}+\left(\frac{2k}{d}\right)^2\theta^2\right\}$$

When $s_F=0$ and $k^2=\frac{1}{12}t^2$ (unstiffened cover), this formula reduces to that stated in Section 2, where the expressions for K_1 and K_2 in terms of θ are also quoted.

Wrinkling of the multi-web structure is very little

influenced by frames, because the half-wavelength of buckle will normally be far less than the frame spacing. This contravenes the conditions stated above which lead to the term $\frac{1}{2}(ds_F/at\theta^2)$, and, if the half-wavelength of buckle is a sub-multiple of the frame spacing, this term is nullified. With moderate values of s_F/a the term is in any case small, and it can always be reduced to zero by slight change of wavelength of buckle, which may affect the critical stress for wrinkling only very slightly. Accordingly the effect of frames may always be disregarded.

In the absence of webs ($s_W=0$) the condition for wrinkling reduces to

$$\left(\frac{f}{E}\right)^2 = \frac{2k^2 s_F}{adt} + \left(\frac{2k}{d}\right)^4 \theta^4$$

The least value of f then corresponds to the least possible value of θ, that is to the longest possible wavelength. This is limited by the total length of the beam, but it suffices to conclude that the critical stress is not less than $(2k^2 s_F/adt)^{\frac{1}{2}}$. For covers of flat sheet unstiffened $k^2=\frac{1}{12}t^2$ and the critical stress is rather more than $0{\cdot}4\,(ts_F/ad)^{\frac{1}{2}}$ as stated in Section 8.

Plane sheet covers stiffened only by multi-webs is an accepted form of structure, but plane sheet covers stiffened only by frames may appear peculiar. Nevertheless, the relative merits of webs and frames as stabilising structures cannot fairly be compared unless the covers are similar. This comparison is represented in Table I for unstiffened covers of flat sheet and for the square cellular box covers mentioned in Section 9. For brevity in this table, f is written for (f/E) and m for (m/Ed^2) or (p/Ed). The mean thickness of the covers is represented throughout by t, so that the wall thickness of the cellular box covers is $\frac{1}{3}t$. The mean thickness of either webs or frames is represented by s. It should be noted that

$$(t/d)=(ft/d)\,f^{-1}=(p/Ed)\,(E/f)=mf^{-1}.$$

APPENDIX II

TORSION AND BENDING

The best means of approach to cases in which deformation of cross section involves also translation of some flats in their own planes is by preliminary consideration of torsion and bending of a complete section when it remains undistorted. The section is supposed to rotate as a whole about a longitudinal axis Ox through the angle $\theta=\theta_m \sin(\pi x/\lambda)$. Then any flat of which the perpendicular distance from this axis of rotation is p acquires a curvature $p\,(d^2\theta/dx^2)=-(\pi/\lambda)^2 p\theta_m \sin(\pi x/\lambda)$, and therefore across the lateral width s of this flat the axial stress f varies linearly in accordance with the relation

$$df/ds=E\,(\pi/\lambda)^2 p\theta_m \sin(\pi x/\lambda)^*.$$

It follows that the difference between the stress f_1 and f_2 at two points l apart on the flat is Kpl, where

$$K=E\,(\pi/\lambda)^2\theta_m \sin(\pi x/\lambda);$$

and the product pl is twice the area of the triangle formed by the two points on the flat and the centre of rotation.

*This inference assumes that the flat is simply bent. The assumption is justifiable provided that λ is greater than (say) three times the whole width of the flat; but over shorter wavelengths shear deformation will contribute appreciably to the curvature and the axial direct stresses f will be reduced.

If the two points are (y_1, z_1) and (y_2, z_2) and if the centre of rotation is (y_0, z_0) this (double) area is

$$\begin{vmatrix} y_0 & y_1 & y_2 \\ z_0 & z_1 & z_2 \\ 1 & 1 & 1 \end{vmatrix} = y_0(z_1-z_2)+z_0(y_2-y_1)+y_1z_2-y_2z_1.$$

Hence

$$(f_2/K+z_2y_0-y_2z_0)-(f_1/K+z_1y_0-y_1z_0)=y_1z_2-y_2z_1,$$

and in general $f/K+zy_0-yz_0=f_0/K$, where f_0 is the stress corresponding to rotation about the origin ($y=0$, $z=0$), which for the moment is left undefined.

The energy associated with the system of axial stresses f is $\frac{1}{2E}\int\int f^2 t\,ds\,dx$, where t is the thickness of section (which may vary with s) and the integral with respect to s is taken along the length of the centre line. The integration along the axis Ox is also indicated for completeness, but of course this integration merely results in the factor $\frac{1}{2}$ which represents the average value of $\sin^2(\pi x/\lambda)$; in what follows no further reference to the axial direction need be made, except of course in so far as the variation of stress axially is represented by the half-wavelength λ.

By substitution for f in terms of f_0, the energy

$$\frac{1}{2E}\int f^2 t\,ds = \frac{1}{2E}\int \{f_0+K(yz_0-zy_0)\}^2 t\,ds$$

$$= \frac{1}{2E}\int f_0^2 t\,ds + \frac{K}{E}z_0\int f_0 yt\,ds - \frac{K}{E}y_0\int f_0 zt\,ds +$$

$$+\frac{K^2}{2E}\left\{z_0^2\int y^2 t\,ds - 2y_0z_0\int yzt\,ds + y_0^2\int z^2 t\,ds\right\}.$$

Then the mean value of f_0 may be chosen so that $\int f_0 t\,ds=0$ and the origin ($y=0$, $z=0$) associated with f_0, from which y_0 and z_0 are to be measured, may be chosen so that $\int f_0 yt\,ds=0$ and $\int f_0 zt\,ds$. At the same time as origin for y and z (as they appear explicitly in the integrals) the centre of section may be retained; because $\int f_0 t\,ds=0$, so that a change of origin of y and z does not affect the values of $\int f_0 yt\,ds$ and $\int f_0 zt\,ds$.

Thus finally the energy (per unit length axially) or torsion-bending about the axis (y_0z_0), measured from the shear centre, is

$$\tfrac{1}{4}E\,(\pi/\lambda)^4\theta_m^2\times(\Gamma_0+z_0^2 I_{yy}-2y_0z_0I_{yz}+y_0^2I_{zz})$$

where $I_{yy}=\int y^2 t\,ds$, $I_{yz}=\int yzt\,ds$ and $I_{zz}=\int z^2 t\,ds$ are the ordinary section moduli* and $\Gamma_0=\int (f_0/K)^2 t\,ds$ under the conditions $df_0/ds=p_0$, $\int f_0 t\,ds=0$, $\int f_0 yt\,ds=0$ and $\int f_0 zt\,ds=0$. The last two conditions define the position of the shear centre from which the perpendicular distances p_0 are measured.

*I_{yy} is the moment of section about the z-axis, that is in the y-plane. By substituting $y'\cos\theta+z'\sin\theta$ for y and $-y'\sin\theta+z'\cos\theta$ for z it follows that

$$I'_{yy}+I'_{zz}=I_{yy}+I_{zz}$$

$$I'_{yy}+I'_{zz}=(I_{yy}-I_{zz})\cos 2\theta+2I_{yz}\sin 2\theta$$

and

$$2I'_{yz}=-(I_{yy}-I_{zz})\sin 2\theta+2I_{yz}\cos 2\theta$$

so that by choosing $\tan 2\theta=2I_{yz}/(I_{yy}-I_{zz})$ the principal axes of section can be defined and the cross product term I'_{yz} eliminated. However it is usually more convenient to retain the general axes Oyz, because the choice of axes may be subject to other considerations.

The resistance to the twist $\theta_m \sin(\pi x/\lambda)$ arising from torsion-bending is thus represented by a distributed moment $M \sin(\pi x/\lambda)$ per unit length axially, where

$$M/\theta_m = E(\pi/\lambda)^4 (\Gamma_0 + z_0^2 I_{yy} - 2y_0 z_0 I_{yz} + y_0^2 I_{zz}).$$

To this must be added the term $GJ(d^2\theta/dx^2) = GJ(\pi/\lambda)^2$, which represents the resistance to pure twist. For a closed section the ratio of the torsion modulus J to the area of section A_s is of course proportional to the area enclosed by the tube, but for any open section this ratio is proportional only to the square of the mean wall thickness.

If the section is subjected to an axial stress f_x this gives rise to a distributed moment, acting in the same sense as θ, $f_x \int r(d^2\theta/dx^2) r t ds$, where r is the distance of a point in the section from the centre of rotation and the integral is taken over the cross section. The integral $\int r^2 t ds$ may be written in the form $J_p + A_s r_0^2$, where J_p, the polar moment about the centre of section, $= I_{yy} + I_{zz}$, and A_s is the area of section and r_0 is the distance between the centre of section and the axis of rotation. If the shear centre coincides with the centre of section $r_0^2 = y_0^2 + z_0^2$, but this condition will not usually be fulfilled.

TORSIONAL AND FLEXURAL INSTABILITY OF SIMPLE STRUTS

Before proceeding to discuss torsional and flexural instability of stringers attached to sheet, it is useful to review the application of the basic formulae to the case of the unsupported strut. The total stiffness to rotation about the axis $y_0 z_0$ is

$$\{GJ - f_x(J_p + A_s r_0^2)\}(\pi/\lambda)^2 + E(\pi/\lambda)^4 (\Gamma_0 + z_0^2 I_{yy} - 2y_0 z_0 I_{yz} + y_0^2 I_{zz})$$

and this stiffness is reduced to zero, so that buckling begins, when

$$f_x = f_c = \frac{GJ + E(\pi/\lambda)^2 (\Gamma_0 + z_0^2 I_{yy} - 2y_0 z_0 I_{yz} + y_0^2 I_{zz})}{J_p + A_s r_0^2}$$

In the case of the free strut there is no reason to use other than the principal axes of section; therefore it is presumed that this conversion has already been effected so that $I_{yz} = 0$.

If the shear centre lies on the principal axis Oy at a distance e from the centre of section, the formula for f_c takes the form

$$f_c = \frac{A + Bz_0^2 + Cy_0^2}{H + (y_0 + e)^2 + z_0^2}, \text{ where } A = \{GJ + E\Gamma(\pi/\lambda)^2\}/A_s$$

$$B = \pi^2 E k_y^2/\lambda^2, \quad C = \pi^2 E k_z^2/\lambda^2 \text{ and } H = J_p/A_s.$$

One critical value is of course $B = \pi^2 E k_y^2/\lambda^2$ when $z_0 \longrightarrow \infty$ and the strut simply bends in the y-plane. The other critical values have $z_0 = 0$ and $f_c = (A + Cy_0^2)/\{H + (y_0 + e)^2\}$, of which the principal values are

$$f_c = \tfrac{1}{2}\left[C + \frac{A}{H} + \frac{Ce^2}{H} \pm \left\{\left(C - \frac{A}{H}\right)^2 + 2\left(C + \frac{A}{H}\right)\left(\frac{Ce^2}{H}\right) + \frac{C^2 e^4}{H^2}\right\}^{\frac{1}{2}}\right].$$

If $e \equiv 0$, these values are $f_c = C$, when $y_0 \longrightarrow \infty$, and the buckle is pure flexure in the z-plane, or $f_c = A/H$ when $y_0 = 0$ and the buckle is pure torsion about the centre of section. On the other hand, if $e \neq 0$, the least value of f_c is less than either C or A/H and y_0 is finite, so that the buckle is a combination of both torsion and flexure. If the shear centre does not lie on either principal axis all modes of buckle involve torsion and bending in both planes.

The parameters A, B and C above all decrease uniformly as λ increases. In consequence buckling always occurs over as long a wavelength as possible and λ may be replaced by the length l between adjacent sections which may be regarded as simply supported. However, in practical cases it is usually simpler to distinguish l as the length between adjacent sections which remain unrotated (in axial planes) and unwarped, in consequence either of applied restraint, as at the platens of a testing machine, or of symmetry, as at the mid-length of a strut so tested. It is conceivable that loading conditions can be such as to render the length l different for the bending and torsion modes, but in most practical cases the same length will be common to all modes. In any case, of course, in dealing with combined modes the same value of λ must be used.

TORSIONAL AND FLEXURAL INSTABILITY OF A STRINGER ATTACHED TO SHEET

In the case of a stringer attached to sheet, the axis of rotation is practically bound to lie in the mid-plane of the sheet; because any axis lying out of this plane would involve curvature of the sheet in its own plane and this mode of distortion is of course strongly resisted. Moreover, the plane of the attached flange of the stringer is separated from the plane of the attached sheet only by the average thickness of the two components, so that this attached flange remains practically unbent in its own plane and the attachment between sheet and stringer is subject to no stress on this account.

On the other hand, if the axis of rotation does not lie in the plane of the stringer web*, the web is bent in its own plane and the resulting axial extension and compression of the attached flange is communicated to the sheet. In consequence I_{zz} must be increased by the addition of the term $A_s \eta b t c^2/(A_s + \eta b t)$, where A_s is the area of the stringer section, c is the height of its centre of section above the mid-plane of the sheet, b is the stringer spacing and t is the thickness of the sheet cover; η is a factor less than unity, which represents the effect of shear lag in the sheet cover and/or the effect of prior buckling of the sheet cover (in between stringers) in reducing its resistance to variation of axial stress.

In respect of shear lag η is a function only of λ/b and decreases uniformly with λ; for $\lambda/b < 2$, a reasonable approximation is $\eta = 0{\cdot}35(\lambda/b)$ and for $\lambda/b > 2$, $\eta = 0{\cdot}60 + 0{\cdot}05(\lambda/b)$ (subject of course to the overriding limit $\eta \not> 1$). In respect of prior buckling η varies from about $\frac{1}{2}$ immediately after first buckle to 0·3 or even less when the buckle is well developed; but these values apply only when λ/b is moderately large (> 2 say). Interaction of both buckling and shear lag is very difficult to assess, but it is appreciable only in the middle range of λ/b; when λ/b is less than unity only the shear lag effect need be considered and similarly when λ/b is greater than 3 shear lag need be represented only so long as the sheet remains unbuckled. It is unfortunate that practical interest is probably greatest just in the range $1 < \lambda/b < 3$ for which the effect of interaction is most uncertain. However, the value of η will seldom have a dominant effect, and for many purposes it will suffice to take for a slightly buckled sheet $\eta = 0{\cdot}4$ irrespective of the value of λ.

Subject to the amendment of I_{zz} by the addition of the term representing the stiffening due to the sheet the total stiffness to rotation of a stringer may be represented by addition of the (two) appropriate μ-terms for the plates on either side of the stringer to the expression

$$[GJ - f_x\{J_p + A_s(c^2 + y_0 + e^2)\}](\pi/\lambda)^2 + E(\pi/\lambda)^4 [\Gamma_0 + z_0^2 I_{yy} - 2y_0 z_0 I_{yz} + y_0^2\{I_{zz} + A_s \eta b t c^2/(A_s + \eta b t)\}]$$

*This is not a precise statement of the requirement, but it suffices for the present purpose.

which represents the torsional stiffness of the stringer itself. In this expression z_0 is the distance of the shear centre of the stringer section from the mid-plane of the sheet, and in most practical cases $z_0=c$. For the symmetrical Zed-section also $e=0$. In order to avoid unnecessary complication attention will henceforward be restricted to this case and in addition the term $I_{zz}+A_s\eta btc^2/(A_s+\eta bt)$ will be represented simply as I'_{zz}.

The μ-terms for the plates, represented in Data Sheets 02.01.28, and so on, already include allowance for the effect of the end stress f_x in reducing the stiffness of the edges of the plates to rotation, and the critical stress f_c may be computed from the formula

$$f_c=\frac{GJ+E(\pi/\lambda)^2(\Gamma_0+c^2I_{yy}-2cy_0I_{yz}+y_0^2I'_{zz})+2\mu(\lambda/\pi)^2}{J_p+A_s(c^2+y_0^2)}$$

by first using the value of μ consistent with estimated values of f_c and λ and subsequent adjustment. Variation of μ with f_c and λ in the probable range of values of b/λ is slight, so that this process of trial and error involves no great labour, but equally it should be feasible to represent the variation of μ in a form such as

$$\mu=\mu_0+(\alpha-\beta f_x)(b/\lambda)^2$$

and then to regroup the basic equation so that μ_0 and α remain in the numerator while β is transferred to the denominator.

From the form of the expression for f_c it will be seen that it has a minimum value $[GJ+2\{E\Gamma\times 2\mu\}^{\frac{1}{2}}]/J_p'$ when $(\lambda/\pi)^4=(E\Gamma/2\mu)$*. In many practical cases this value of λ will exceed the effective free length l of the panel, and in such cases l should be substituted for λ in the basic formula. On the other hand, it is advisable to check that the critical value of λ does exceed l.

It remains to discuss the choice of the value of y_0; but this question cannot properly be considered except by reference to a complete construction, such as a complete wing cover or at least a test panel.

TORSION AND FLEXURAL INSTABILITY IN A COMPLETE PANEL

In a complete wide panel consisting of a number of similar stringers uniformly spaced, instability may occur by adjacent stringers rotating equally in alternate senses or by their all rotating equally in the same sense.

In the first case the appropriate value of μ for the sheet cover is μ_2 (Data Sheet 02.01.31). Moreover, whatever the value of y_0 the lateral deflection of the sheet cover is alternately in opposite senses at spacing equal to the stringer spacing b. Accordingly μ_2 represents the whole effect of the sheet. In the second case the appropriate value of μ is μ_3 (Data Sheet 02.01.33), but in addition the whole width of the sheet is deflected out of its original line through a distance $y_0\theta_m\sin(\pi x/\lambda)$. The resistance of the sheet cover to this deflection is already represented in the amendment of I_{zz} to I'_{zz}; but in addition the end stress f_x gives rise to lateral loading $f_xbty_0\theta_m(\pi/\lambda)^2$, which may be represented as a negative contribution to the resistance to twist $-f_xbty_0^2(\pi/\lambda)^2$. Therefore the term bty_0^2 must be added to the denominator of the expression for f_c. If the sheet cover is already buckled in plates between stiffeners, this term should be reduced in the ratio f_a/f_e, where f_a is the average stress in the plates and f_e, the edge stress, is identical with f_x, but in a buckled sheet the appropriate values of μ are also modified, and the problem is considerably complicated.

*The sense of Γ and J_p' will be clear by comparison with the original form.

In both cases the expression for f_c takes the form

$$f_c=\frac{A-By_0+Cy_0^2}{H+y_0^2}$$ and the minimum value is

$$f_c=\tfrac{1}{2}\left(\frac{A}{H}+C\right)-\tfrac{1}{2}\left\{\left(\frac{A}{H}-C\right)^2+\frac{B^2}{H}\right\}^{\frac{1}{2}}$$

$$\text{when } y_0=\frac{A-CH}{B}+\left\{\left(\frac{A-CH}{B}\right)^2+H\right\}^{\frac{1}{2}}$$

If $A/H>C$ and B is small, y_0 is large, f_c is slightly less than C and the buckle is almost pure flexure.
If $A/H<C$ and B is small, y_0 is small, f_c is slightly less than A/H and the buckle is almost pure torsion.
If $A/H=C$, $y_0=H^{\frac{1}{2}}$ and $f_c=C-B/2H^{\frac{1}{2}}$.

In these formulae

$$\frac{A}{H}=\frac{GJ+E(\pi/l)^2(\Gamma_0+c^2I_{yy})+2\mu(l/\pi)^2}{J_p+A_sc^2}$$

$$B=\frac{2E(\pi/l)^2cI_{yz}}{A_s}$$

when adjacent stringers rotate in opposite senses

or $$\frac{2E(\pi/l)^2cI_{yz}}{A_s+bt}$$

when all the stringers rotate the same way

and $C=E(\pi/l)^2\{I_{zz}+A_s\eta btc^2/(A_s+\eta bt)\}/A_s$ or (A_s+bt)

and $H=(J_p+A_sc^2)\text{Y}A_s$ or (A_s+bt).

The effect of interaction between bending and torsion is best represented graphically as in Fig. 5. By the use of this diagram application of the formulae above to define f_c for an unbuckled panel should be straightforward, using η for shear lag appropriate to the value of b/l and for large values of l checking that $\lambda=l/2$ (with η corresponding to $2b/l$) does not lead to a lower value of f_c. For a slightly buckled panel the procedure is also straightforward using $\eta=0{\cdot}4$ (say) and substituting $A_s+\eta'bt$ for A_s+bt, where $\eta'=(f_a/f_e)=\frac{1}{2}(1+f_b/f_c)$ approximately, where f_b is the stress at which the plates buckle. If f_b is very much less than f_c, so that the plates have already developed deep buckles before the stringers are liable to become unstable, the corrugation of the plates may considerably increase their resistance to lateral bending over wavelengths greater than the wavelength of the corrugations. The effective values of μ may be thus greatly increased, particularly in the antisymmetrical mode (μ_2); there is at present no ready means to assess this effect quantitatively. Neglect of the effect leads to an underestimate of f_c, particularly for the torsional mode; but since the effect will be marked only in fuselage type construction the error may seldom be of much practical importance.

INTERACTION BETWEEN LOCAL AND TORSION-BENDING MODES

The stress systems associated with torsion-bending modes are all virtually constant through the thickness of the wall of each component flat; whereas the stress systems associated with local deformation all vary linearly through the wall thickness and have mean value zero. Accordingly there can be no interaction in respect of these stress systems. On the other hand, in respect of the effect of the axial stress f_x local deformation does interact with both torsion and bending. The nature of this interaction is best illustrated by reference to a simple example.

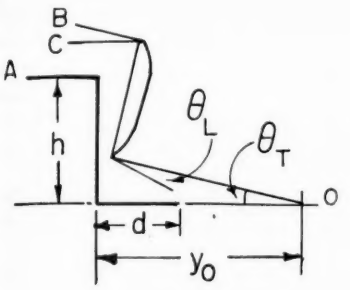

FIGURE 11.

In Fig. 11 the symmetrical Zed-section stringer A is presumed to rotate through the angle θ_T about the pole O lying in the plane of one flange and distant y_0 from the foot of the web. The section is thus brought without distortion into the position B and it is then distorted into the position C; for the purposes of this illustration in this local distortion both flanges are assumed to remain straight and rotate through the angle θ_L in opposite senses and the web is assumed to be bent so that its lateral deflection is $\theta_L x(h-x)/h$ where x is the distance along the web from one corner. Then the integral over the section of the square of the total deflection out of the original position is

$$\int_0^d \{(y_0-x)\theta_T - x\theta_L\}^2 t\,dx + \int_0^h \{x\theta_T + x(h-x)(\theta_L/h)\}^2 t\,dx +$$

$$+ hty_0^2\theta_T^2 + \int_0^d \{(y_0+x)\theta_T - x\theta_L\}^2 t\,dx + dth^2\theta_T^2$$

$$= \left\{\left(\frac{1}{3}h^3 + h^2 d + \frac{2}{3}d^3\right)t + A_s y_0^2\right\}\theta_T^2 +$$

$$+ \left(\frac{1}{6}h^3 - 2y_0 d^2\right)t\theta_T\theta_L + \left(\frac{1}{30}h^3 + \frac{2}{3}d^3\right)t\theta_L^2$$

The coefficient of θ_T^2 is precisely $J_p + A_s r_0^2$ as previously derived. The coefficient of θ_L^2 represents the corresponding negative contribution to μ_L, the effective stiffness of the stringers to rotation about the foot of the web associated with local deformation; but in this case the expression is not exact, because the distorted form assumed in the present section is not the correct form. The appearance of a term in $\theta_T\theta_L$ of which the coefficient varies with y_0 implies interaction of local with both torsion and bending (that is, torsion about any axis).

The total energy of the twisted and distorted stringer may then be represented in the form

$$\tfrac{1}{2}\mu_T\theta_T^2 + \tfrac{1}{2}\mu_L\theta_L^2 - K\theta_T\theta_L,$$

where μ_L and μ_T relate to purely local and purely torsional deformations and only the value of K has yet to be defined. For the symmetrical Zed-section attached to sheet

$$\mu_T = [GJ - f_x\{J_p + A_s(c^2+y_0^2)\}](\pi/\lambda)^2 + E(\pi/\lambda)^4(I'_0 + c^2 I_{yy} - 2cyI_{yz} + y^2 I'_{zz})$$

$$\mu_L = D_1 + \frac{\frac{1}{2}(H_2+H_3)D_1 + H_2H_3}{D_1 + \frac{1}{2}(H_2+H_3)}$$

*D_1 represents the value of μ_1 for the flange, and H_2 and H_3 represent the values of μ_2 and μ_3 for the web. The rotation at the base of the web being θ and that at the top of the web ϕ, it follows that

$$T_\phi = 0 = D_1\phi + H_2\tfrac{1}{2}(\phi+\theta) + H_3\tfrac{1}{2}(\phi-\theta)$$

and

$$T_\theta = D_1\theta + H_2\tfrac{1}{2}(\theta+\phi) + H_3\tfrac{1}{2}(\theta-\phi).$$

Hence by elimination of ϕ,

$$\mu_L = T_\theta/\theta = D_1 + \tfrac{1}{2}(H_2+H_3) - \frac{\frac{1}{4}(H_2-H_3)^2}{D_1 + \frac{1}{2}(H_2+H_3)}.$$

By reference to Fig. 11, since the coefficient of θ_T^2 is identified with $-\{J_p + A_s(c^2+y_0^2)\}$, as it appears in the expression for μ_T, equally the coefficient of $\theta_T\theta_L$ may be identified with $2K$. Thus, approximately

$$K = \left(\frac{1}{12}h^3 - y_0 d^2\right)t(\pi/\lambda)^2 f_x,$$

the formula being inaccurate because the form of distortion assumed for local buckling is not quite correct. Greater accuracy could be achieved by approximating more closely to the true form, but K has only a minor influence so that this improvement seems unnecessary.

Writing the total energy $\frac{1}{2}\mu_T\theta_T^2 + \frac{1}{2}\mu_L\theta_L^2 - K\theta_T\theta_L$ in the form $\frac{1}{8}\mu_T(S+D)^2 + \frac{1}{8}\mu_L(S-D)^2 - \frac{1}{4}K(S^2-D^2)$, where $S=\theta_T+\theta_L$ and $D=\theta_T-\theta_L$ by differentiating with respect to S and D, it follows that

$$M_s = \tfrac{1}{4}\mu_T(S+D) + \tfrac{1}{4}\mu_L(S-D) - \tfrac{1}{2}KS$$

and

$$0 = \tfrac{1}{4}\mu_T(S+D) - \tfrac{1}{4}\mu_L(S-D) + \tfrac{1}{2}KD$$

Then by elimination of D,

$$\mu_C = (M_s/S) = (\mu_T\mu_L - K^2)/(\mu_T + \mu_L + 2K)$$

In many cases, however, the approximation

$$\mu_C = \mu_T\mu_L/(\mu_T+\mu_L)$$

is likely to prove sufficiently accurate.

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DISCUSSION

E. D. Keen (Chief Designer, Sir W. G. Armstrong Whitworth Aircraft Ltd., *Fellow*): Mr. Cox had devoted most of his working life to a detailed study of the stability problems of structures of all kinds with special reference to aircraft structures. He would like to say that from the Society's point of view, as a member and for many years the Chairman of the Structures Committee, the high standard of the Structures Data Sheets owed a great deal to the guidance and industry of Mr. Cox. The Society's Technical staff and his fellow Committee members felt a deep sense of gratitude for Mr. Cox's guidance and practical help.

It had been said that this particular branch of structural design had received more attention than any other single structural subject and the volume of literature relating to it was very great indeed. This was undoubtedly a reflection of the difficulty of the subject since even with all the guidance which Mr. Cox and all the host of other workers could give in this field no designer would rely on a purely theoretical treatment without *ad hoc* test evidence to check the solution. As Mr. Cox had indicated once or twice even then they got some shocks. To some extent of course stability problems had lessened in the design of high speed aircraft with high structural loadings demanding thicker skins, but the advent of steel structures from temperature consideration reintroduced the problems formerly associated with thin light alloy skins which triggered off the very considerable research programme which had culminated in the present lecture; and if this was not enough thermal effects must be added, both from the point of view of additional induced strains and their effect on material properties.

In the introduction, the lecturer's negative maxim seemed to require a little more explanation. Mr. Cox had referred to arts and sciences and so one, but he would like to point out that extensive use of digital computers was now being made in cutting out loading systems in a very large variety of cases and he wondered whether this would not help in turning art into a little bit of science in this respect. They would all like Mr. Cox to enlarge a little more on this negative maxim.

He had one or two hobby horses in this field, perhaps it was because he had turned from being a practising structural engineer to super critical designer, but it had always seemed to him that too little attention had been paid to the behaviour of thin sheet structures beyond the point of buckling. After all, they had to prove structures to the ultimate strength, these were the design rules of the moment, right or wrong. Problems involving forced distortions of stringers by a buckled sheet were admittedly very complex but they could have devastating results in practice compared with theoretical predictions. This was particularly true in cases where skin thickness was large compared with stringer thickness and f/f_c was relatively high. Another extremely difficult subject was the problem of joining elements of stiffened skin together and trying to express effects of different methods scientifically. He would like to "stick his neck out" and say that he considered that it was true to say no theoretical treatment could so far accurately assess the improvement which was practically obtained and instinctively expected by adhesives or integral construction as compared with riveted joints.

He hoped that Mr. Cox did not think that he was complaining about this, he was pointing out that there were many gaps to fill which he was sure Mr. Cox knew already. From his personal knowledge of the lecturer's realisation of these practical problems he was sure he would continue to strive on behalf of all the structural engineers for their solution.

Professor W. S. Hemp (College of Aeronautics, *Fellow*): He found it difficult to speak about this subject because it was a deep and profound one; at least the background to it was. One could speak more about the detail, but that was possibly something which might be left. It would be better to talk about the philosophy which Mr. Cox had referred to. He particularly welcomed the contribution he was making in this paper, because it was on a subject which he thought was very important for the theory of structures. Most of them in the theory of structures had, over the years, been concerned largely with the problem of "given a structure, what stresses occur in it when certain loads are applied to it." The problem of design was "given the loads, what structure are we to put in?" The structure had to be satisfactory from the stressing point of view—it had to be strong enough—and it had to be of minimum weight. That was the *real* problem of the theory of structures and quite honestly little had been done along those lines. He knew that one could point to a number of special studies of which this paper was an example, but that did not answer the general question, and did not solve the general problem as to how to fill in space, where to put the structure in the best possible way. That was the sort of objective one ought to have in advancing the theory of structures and it might be possible, on the basis of some work which had been done long ago, to solve that class of problem in the future. Mr. Cox made mention of this general background, by way of explanation. An account of this ought really to come from Mr. Cox.

In 1904 there was a paper written by a man named Michell in connection with a thrust block. He wrote a paper that nobody noticed. This paper was concerned with the optimum design of frame structures. It was concerned with the problem of how to dispose the members of the frame for given loads, so that the total weight of the structure should be a minimum. A few years ago Mr. J. Foulkes at Cambridge drew Mr. H. L. Cox's attention to it. Mr. Cox had been thinking about this, working on it and giving papers on it since, and this paper, at least the earlier remarks in it, connected with general philosophy and Michell's point of view.

Michell only solved the problem of frame structures. The problem now, of course from an aircraft point of view, was that of shell structures and other more general kinds of structures than frame ones. Mr. Cox had emphasised that the problem in relation to aircraft was largely a matter of how to reinforce the skin. Most of the weight ought to be put away from the middle of the wings, from the middle of the fuselage for various

reasons, not only structural. The main problem was how to stabilise it, but he thought there might still be some place for the considerations the Michell paper was concerned with, that was to say, varying the thickness of the skin in such a way as to reduce the weight by that last 2 or 3 per cent, which might be vitally important in some of the modern aeroplanes and missiles.

J. Taylor (Structures Dept., R.A.E., *Fellow*): Mr. Cox wrote "true Brazier instability of an I-beam occurs only after the web has compressed by one quarter of its depth." The Brazier effects that he had known, which admittedly were not entirely on I-beams, had occurred under very small compressions. Could Mr. Cox say what was the correlation between the theoretical one of a movement of a quarter of its total depth and the actual one which, as far as he knew, was microscopic movement? Was it entirely the difference between an I-beam, as defined by Mr. Cox, and an aircraft structure where the webs were so far apart that the instability occurred at a large distance from the webs?

E. J. Catchpole (Aero Research Ltd., *Associate Fellow*): In his written paper (Section 9), Mr. Cox seemed to express some surprise at the inefficiency of the panel with unflanged integral stiffeners as compared with the other panels he mentioned (Z stringer, Y stringer and sandwich). He thought this was not really surprising since in all the other constructions mentioned there was a substantial flange away from the skin. For this reason the marked difference in efficiency was surely to be expected.

Again referring to the written paper, the section on honeycomb sandwich structure (Section 10), introduced a coefficient β. Taking the definition of this as

$$\beta = \frac{G_L}{G\rho} \quad \text{where} \quad G_L = \text{the shear modulus of the core in the longitudinal (foil) direction,}$$

one found from the published data (Aero Research Honeycomb Information Sheet 1B), that the average value for β was 0·32 and in fact the lowest value given was 0·266. A more recent investigation had been made as a combined effort between the Aeronautics Department of Imperial College, London, and Aero Research Limited and this had shown a theoretical value of β in the range 0·6 to 0·67 and test values close to this (it was intended to publish this work in due course). He noted that a minimum value of β of 0·10 was mentioned in Mr. Cox's paper and thus it was clear that this minimum value was substantially exceeded. In other words, using the longitudinal honeycomb shear stiffness, β was already high and therefore Mr. Cox's proposal that it was preferable to increase the longitudinal shear stiffness rather than to maintain high transverse stiffness (the theoretical value for β in this case was 0·4) might perhaps not be applicable. Certainly he was a little surprised that Mr. Cox gave little importance to transverse shear stiffness since he had always considered that one of the main advantages of a honeycomb sandwich was that sufficient support might be obtained from the sides of the panel (*i.e.* from the "spars") to enable a great reduction in the number of transverse ribs. Of course, some ribs might still be necessary for the input of local loads, for tank boundaries, and so on, but one could certainly anticipate a very substantial reduction. He wondered whether Mr. Cox would care to make some further comments about transverse shear stiffness. He realised that the shear stiffness of honeycomb was rather an important factor and this had really been brought out by Mr. Cox's paper. The sparseness of, and the apparent inconsistencies in, the existing data on this property led to the investigation mentioned.

Mr. Cox said that while frames needed a certain minimum stiffness, no one seemed to have pointed out what governed this requirement. He was sure that Mr. Cox was familiar with the work of Shanley (*Journal of the Aeronautical Sciences*, October 1949), in which he found a criterion for the minimum stiffness of fuselage frames to prevent overall instability. Would Mr. Cox comment on that work?

R. H. Sandifer (Assistant Chief Designer (Structures), Handley Page Ltd., *Fellow*): He would like to record his appreciation of the lecture; he thought it made a great contribution to their knowledge.

In Section 2 no mention was made of the lateral (or torsional) instability of the tension flange of the beam. In practice the tension flange of a beam, particularly a deep beam, might collapse sideways due to the tendency of this flange to straighten out, that was to reduce its own curvature. This was particularly so if the flanges were unsymmetrical relative to the centre line of the web. Common examples were floor beams and deep stiffeners to bulkheads under pressure. He did not think this phenomenon was quite the same as the torsional instability of stringers in compression; perhaps Mr. Cox would like to comment on this.

In regard to Sections 6 and 7, dealing with spanwise members and ribs, he felt that the cost of ribs, whatever their detail design, was high because in most cases they were less efficient than multi-web designs. This was perhaps inevitable when one considered that the overall purpose of the wing structure was to carry the external loads to the root of the wing and the most direct path was by spanwise members rather than by chordwise members (such as ribs) between the two comparatively widely-spaced spars, and only then to transfer the load in a spanwise direction. One must reach a compromise on this, but he thought perhaps that was the tendency.

Concerning Section 10, on sandwich construction, in regard to the lecturer's comment about low loadings on sandwich construction, he thought there was a lower limit of usefulness, and that was set by the fact that there were three sheets forming the sandwich, or two sheets and some core, and therefore when one got down to low loadings, the actual thicknesses of the sheets became a little impractical.

He would like to offer one general suggestion, and that was that he felt one would have a better appreciation of the notation used in the paper and of the problems faced, if the author would add a few elementary line diagrams of the beams, boxes, and so on, and dimension them with the notation quoted. It would help one to visualise the many symbols that were necessary in a work of this kind.

Sir George Edwards (Chairman): He thanked Mr. Cox very much for the work he had put into the paper

and the series of supplementary lectures given in the discussion; he would like to encourage people to make written contributions to this, a profound subject which did not exactly lend itself to light-hearted "off the cuff" comments; he believed that if Mr. Cox had started with the ending he might have caused a good deal more controversy during the course of the opening half hour.

MR. COX'S REPLY

Professor Hemp: The fundamental theory was a subject on which he could talk for ever, particularly that part of it which concerned his negative maxim. This was a branch of logic, not mathematics, and logic was a much neglected subject.

Supposing that one needed a structure which on one occasion was to carry a loading system A and on another occasion the loading system B. As Professor Hemp had pointed out Michell did indeed provide rules to design structures for single specified loading cases. These rules were not easy to use but with a little grind they could be applied to devise an optimum structure for loading system A or again to devise another optimum structure for loading system B. Neither of these optimum structures need be unique; there might be several or whole classes of structures all of the same weight. But some loading cases did lead to unique solutions and so for the moment he would restrict his attention to that class.

Then for loading A they had a unique structure which they might designate S_A. Now they might design another structure with the same general layout to carry loading B and designate this structure S_B. To fix ideas they might think of both S_A and S_B as similar bar-frame structures differing only in the areas of section of the bars, which in each structure were chosen to fulfil the condition of constant stress under loading A or loading B. (If any bars in A were actually absent from B they were rather to be thought of as present but having zero area of section; in the extreme of course all members of A might have zero section in B and vice versa, but in practical cases there would usually be a fair proportion of common members.)

Now they might designate a composite structure S_{AB} merely by selecting the heavier members from S_A and S_B and expect this composite structure to carry either loading A or loading B and moreover to afford a reasonable approach to the lightest structure which would serve the dual purpose. In fact structure S_{AB} might be unable to carry either loading, because in S_A under loading A every bar was stressed to its limit; if then they increased the section of some bars leaving others unaltered it was likely that one or more of these unaltered bars would be overloaded when loading A was applied. Similarly under loading B the members of S_{AB} which were taken from S_B might fail.

There was indeed only one condition in which this manner of approach yielded a logically satisfactory answer, that was the trivial case when S_A was capable of supporting loading B anyway (or of course when S_B could carry loading A). In cases when this condition was not quite fulfilled, the only practical advice was to try S_A or S_B factored a little higher. The only other course was to investigate every possible distribution of the areas of sections of the bars. This was practicable if one had enough leisure and patience, but one needed a lot of both. However, with modern aids to computing this omnibus procedure was now less forbidding.

He had applied the procedure to a simple five-bar problem simply to demonstrate that this logic of dual purpose design was essentially practical. In this example the "obvious" minimum weight would be afforded by a three-bar arrangement, which was not strictly a framework, in that it was stiff only to the two alternative specified loadings and a mechanism to loadings of other types. Yet, after exploration of all possible structures, it proved that this apparently obvious optimum was appreciably heavier than the true optimum, and moreover that the true optimum was always a redundant frame, well balanced in all its proportions.

Mr. Taylor: In the round tube under bending, which was the case first investigated by Brazier, the cross thrust between the tension and compression surfaces resulted in deformation of the cross section from a circle into an ellipse. True instability occurred only when the rate at which this ellipticity developed exceeded the normal increase of bending moment associated with the increase of curvature; in the case of the round tube this condition was not reached until the diameter of the tube in the plane of bending had been reduced by two-ninths of its original value.

In some other forms of section true Brazier instability might occur after far less deformation of the cross section, but he thought Mr. Taylor was probably referring to cases of secondary instability, in which the web structure collapsed under the Brazier loads. For instance, even in the round tube the distortion of the cross section into an ellipse resulted in high bending stresses at the sides of the tube, and final collapse due to yield in these regions would nearly always anticipate true Brazier instability.

Mr. Catchpole: In referring to the balance between transverse and longitudinal shear stiffness of the honeycomb core he was thinking of a conventional design with frames at normal spacing, *i.e.* he was regarding the honeycomb filled sandwich as a direct replacement for ordinary stringer stiffened sheet. If one sought to dispense with the frames or to space them more widely then of course transverse stiffness would be needed.

If the value of β were 0·2–0·3 then certainly there was margin enough to provide some transverse stiffness. Moreover, after a chat with Mr. Tyson and Mr. Robinson at Handley Page, he had since realised that, although the sandwich without frames was equivalent to rib and stringer design, the flange area of the ribs was already available in the covers. In consequence sandwich structure was able to dispense with frames without incurring the weight penalty otherwise introduced by separate ribs.

He did know of the work of Shanley on fuselage frames—and he had published similar analysis of his own—but this was a question of terminology. He always used the word "frame" to denote a braced frame or complete diaphragm; a frame like a fuselage frame he called a rib—in sympathy with human ribs which

were also not very well supported. He recognised that the usual convention had the two the other way round, presumably by analogy with picture frames.

Mr. Sandifer: He was very interested in the type of instability mentioned by Mr. Sandifer and agreed that it appeared distinguishable from torsional instability. Lateral instability of deep beams could be represented as a combination of bending and torsion; but in Mr. Sandifer's case he understood that the compression flange was a continuous sheet, which could not deflect sideways, and that it was only the tension flange which moved laterally. He did not recall any analysis of this case, which certainly merited exploration.

The treatment might follow the lines of the analysis of flexural-torsional buckling described in Appendix II with, of course, the addition of the side loading; but it might also be necessary to consider the effect of the cross thrust in the webs of the beam. This was an additional factor which might bring in an element of local as well as torsional deformation; in particular the combined mode might lead to instability even of a symmetrical beam for which I_{yz} was zero.

In comparing one type of construction with another it was always necessary to establish for each type the value of f_{opt} corresponding to the structure loading coefficient specified. If this value was much in excess of the highest permissible working stress f_m, *i.e.* twice or more, the weight of stabilising structure required was small and there might be little to choose between several types of construction, provided that for each of them $f_{opt} > 2f_m$. At the same time as the structure loading coefficient was reduced the value of f_{opt} fell, and fell more rapidly for the less efficient types of stabilising structure, such as ribs, than for the more efficient ones, such as webs or frames. The detail of such comparison was illustrated in Appendix I.

The point made by Mr. Sandifer was, however, a different one and related to the transfer of shear along the beam. Multi-webs were clearly superior in this respect to ribs or even to frames between spar webs; but this superiority was additional to the greater efficiency of webs as stabilisers to the compression flange. However, in current wing design f_{opt} was usually so high that the choice of type of stabilising structure was unimportant and the merit of one against another was more likely to lie in its efficiency in shear.

General Reply: In conclusion, he wished to thank the President and the several contributors to the discussion both for their appreciative comments and for their most pertinent questions. If he attempted full answers to all the questions raised a paper already overlong would have to be expanded to a book. There was indeed room for two books, one on the general theory of design as described by Professor Hemp, and another on the detail of design to which Mr. Keen had referred.

With regard to attachment of skins to core he did not mean to imply that gluing was always imperfect. He was referring rather to the work of Howard on the effect of initial irregularities in causing local stresses. In any practical sandwich some amplitude of surface irregularities was inevitable and as these developed into wrinkles quite high stresses might be developed locally. The glued joints might hold, but the rather soft material in the honeycomb core itself might give way. It was as well to insure against premature failure from this cause.

The mathematical and logical complexities of the general theory were so fascinating that he would gladly devote the rest of his working life to exploring them. Moreover, practical application of the general theory was not so remote as it might appear; he need only mention Mansfield's work on neutral holes or ask them to look at a wing spar gashed for air-intake to jet engines. As Mr. Keen pointed out modern computing aids rendered possible logical development of even dual purpose designs. What was lacking was programme, and logical programming for thorough exploration of all possible designs demanded a much better understanding of the general theory. He certainly joined with Professor Hemp in urging the importance of work in this field, and he was glad to report that enthusiastic support was offered by others.

At the same time he had so long been closely associated with his fellow members on the Society's Technical Committees that he was well aware that the Industry could not wait for the final "one hoss shay." They had to use the theory as it existed and, when the theoretically perfect structure failed in the *ad hoc* test before they expected, they had to look again at the theory to see where they must have gone wrong. The whole of Appendix II was indeed devoted to this re-examination of basic theory, but he would be the last to claim that all the answers were there yet; such work proliferated in footnotes, which indicated where the ice was *known* to be thin.

It was, however, indicative of their improved understanding of the primary stress system that so much attention was now being directed towards secondary systems. Instability under Brazier loads, comparison between riveted and glued stringers, and reserve factors against wrinkling in honeycomb sandwich structures were all instances of the growing need to assess secondary stresses. In this field the influence of the details of design was paramount; for instance in riveted panels wrinkling depended directly upon the offset of the rivet line from the stringer web (f in Fig. 10). If theory were to assess the effect of all such influences accurately a great deal of detail not only of design but also of production would need to be closely controlled, as for instance the initial irregularities in a curved shell. At the same time he was not prepared to concede to Mr. Keen that alteration of such detail must always lead to improvement in the sense of less structure weight. The trouble in the past had been that the details themselves were ignored; had the dangers inherent in them been recognised and provision made against these risks the engineer's joints might well have proved as good as the metallurgist's or chemist's. The merit lay not in glued or integral construction in themselves but in their avoidance of a type of instability against which provision had not been made.

That last sentence epitomised the whole problem; to imagine all possible modes in which a structure might fail and then to insure that it did not.

Semi-Empirical Methods of Estimating Forces on Bodies at Supersonic Speeds

by

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SUMMARY: Semi-empirical methods are described for obtaining the normal forces and centre of pressure positions of isolated cone-cylinders and ogive cylinders with and without boat tails at supersonic speeds. The data for normal force slope and centre of pressure at zero incidence is, in general, accurate to better than 10 per cent and half calibre respectively. The data for high incidence must be considered speculative although reasonable agreement has been found with the very limited experimental data available.

1. Introduction

Much theoretical work has been done towards determining the forces on an isolated body of revolution at small incidence and at supersonic speeds but the results have usually left much to be desired in terms of accuracy. The limitations of slender body and linearised theories are well known. Hybrid theory[1], the combination of second order theory zero incidence flow with linear theory crossflow, offers improvement only at low supersonic speeds and then only for bodies with short afterbodies because the negative loading some distance along the afterbody predicted by linear theory has not been observed at Mach numbers greater than two. Computations by second order theory of the forces on cones[1] and paraboloids[2] have shown that no great improvement could be obtained by using more complex theoretical methods other than "exact" methods such as linearised characteristics[3]. In this paper the forces on cone-cylinders are obtained by determining the theoretical loading just behind the shoulder of the cone-cylinder combination exactly within the limits of the accuracy of inviscid flow theory using data computed under Kopal[4] (as described in the Appendix) and then assuming an empirical fall-off of loading from the shoulder along the cylinder. Lacking exact solutions to the flow over tangent and secant ogives at incidence similar to those due to Kopal for cones, the forces on tangent-ogive-cylinders have been obtained empirically by correlating available wind tunnel data using the supersonic similarity parameters.

At incidences greater than 3° or 4° the normal forces and centres of pressure cannot be estimated accurately from the zero incidence characteristics due to viscous crossflow effects. The estimation of forces at high incidences is facilitated by the concept of crossflow drag, as first introduced by Allen, even though recent work studying the flow field structure around an isolated body at high incidence has shown the physical picture to be considerably more complex. Allen[5] assumed that the crossflow drag coefficient was constant along the body and equal to 1·2 times an efficiency factor accounting for the effect of finite body finess ratio. Kelly[6] pointed out that this is accurate only for very long bodies and proposed a method which used the data of Schwabe[7] for the build-up of force on a cylinder started impulsively from rest. However the experimentally determined local crossflow drag distribution from bodies at incidence is quite different from that from Schwabe's data so this experimental data is used.

A detailed discussion of various theoretical and empirical methods of estimating normal forces and centres of pressure and comparisons with the methods of this paper and the available experimental data will be published elsewhere.

Received November 1957.

NOTATION

b	length of boat tail	
$C_{D\sigma}$	local crossflow drag coefficient	based on cylinder diameter
C_M	pitching moment coefficient	based on cylinder diameter
C_N	normal force coefficient	based on cylinder diameter
d	diameter of cylinder	
h	nose length	
I	function defined in equation (3)	
J	function defined in equation (5)	
l	length of body	
x	distance from vertex of body	
β	$\sqrt{(M^2-1)}$	
δ	nose semi-angle	
α	incidence	
Δ	increment due to viscous crossflow effects	
Λ	non-dimensional local loading per unit radius per unit incidence at zero incidence	

Suffixes

b	base
BODY	complete body
c.p.	centre of pressure
CONE	cone
CYL	cylindrical portion of body
s	just behind shoulder of cone-cylinder combination

2. Normal Force Slopes and Centres of Pressure at Zero Incidence

2.1. CONE CYLINDERS

The normal force slope $(\partial C_N/\partial z)_{CONE}$ for an isolated cone has been obtained from Ref. 4 and is shown in Fig. 1 as a function of cone semi-angle and free stream

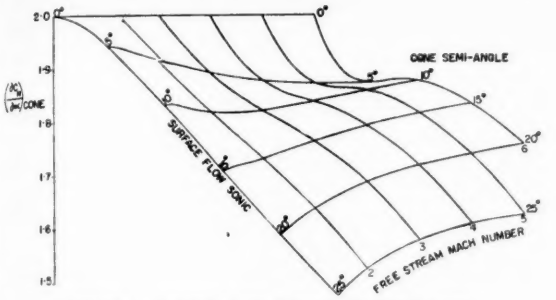

FIGURE 1. Normal force slope of isolated cones.

Mach number. The centre of pressure $(x_{c.p.})_{CONE}$ is given by

$$\left(\frac{x_{c.p.}}{h}\right)_{CONE} = \frac{2}{3}\sec^2\delta \quad . \quad . \quad (1)$$

The loading just behind the shoulder of a cone-cylinder has been obtained by considering the Prandtl-Meyer flow expansion from a cone at incidence onto a cylindrical afterbody (*see* Appendix). Fig. 2 shows the local loading just behind the shoulder Λ_s as a function of nose cone semi-angle and free stream Mach number evaluated from the data of Ref. 4. For the cylindrical afterbody the fall off of local loading from the shoulder to zero at an infinite distance downstream has been determined empirically and is shown in Fig. 3. Integration of the local loading leads to values for normal force slope and centre of pressure position. The total cone-cylinder normal force slope is given by

$$\left(\frac{\partial C_N}{\partial \alpha}\right)_{BODY} = \left(\frac{\partial C_N}{\partial \alpha}\right)_{CONE} + \left(\frac{\partial C_N}{\partial \alpha}\right)_{CYL} \quad . \quad (2)$$

where $$\left(\frac{\partial C_N}{\partial \alpha}\right)_{CYL} = \beta \,.\, \Lambda_s \,.\, I \,., \quad . \quad . \quad (3)$$

and the integral of the local loading ratio I,

i.e. $$\int_h^l \frac{\Lambda}{\Lambda_s} \,.\, dx, \quad . \quad . \quad (4)$$

is shown in Fig. 3 as a function of $(l-h)/\beta d$.

The moment of the forces on the cylinder about the shoulder of the cone-cylinder is given by

$$\frac{d}{l-h}\left(\frac{\partial C_M}{\partial \alpha}\right)_{CYL} = -\beta \,.\, \Lambda_s \,.\, J \,., \quad . \quad (5)$$

where J is the integral of the moment of the local loading

i.e. $$\int_h^l \frac{\Lambda}{\Lambda_s} \,.\, \left(\frac{x-h}{l-h}\right) \,.\, dx \,. \quad . \quad . \quad (6)$$

The body centre of pressure position is given by

$$(x_{c.p.})_{BODY} = \frac{(x_{c.p.})\left(\frac{\partial C_N}{\partial \alpha}\right)_{CONE} + (x_{c.p.})\left(\frac{\partial C_N}{\partial \alpha}\right)_{CYL}}{\left(\frac{\partial C_N}{\partial \alpha}\right)_{BODY}}, \quad (7)$$

where $$\frac{(x_{c.p.})_{CYL} - h}{l-h} = \frac{J}{I} \quad . \quad . \quad . \quad (8)$$

is shown in Fig. 3 as a function of $(l-h)/\beta d$.

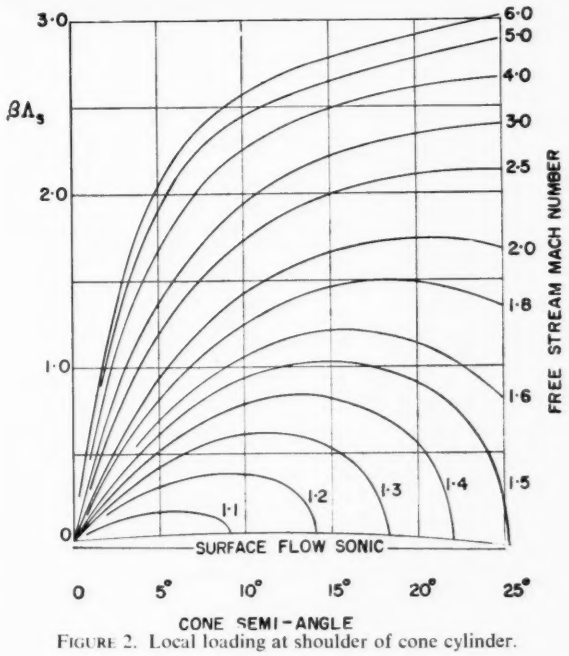

FIGURE 2. Local loading at shoulder of cone cylinder.

For very low supersonic Mach numbers where the flow over the nose cone is no longer conical, linear theory[8, 9] could be used. The normal force slope for cones and cone-cylinders with cylinders of effectively infinite length, *i.e.* $(l-h)/\beta d > 4$ can be obtained[10] without consideration of the manner in which the local loading varies along the body.

Thus $$\left(\frac{\partial C_N}{\partial \alpha}\right)_{CONE} = 2\,[1-A], \quad . \quad . \quad (9)$$

and $$\left(\frac{\partial C_N}{\partial \alpha}\right)_{BODY} = 2\,[1+A], \quad . \quad . \quad (10)$$

where $$A = \frac{\cosh^{-1}\left(\frac{2h}{\beta d}\right)}{\cosh^{-1}\left(\frac{2h}{\beta d}\right) + \frac{2h}{\beta d}\sqrt{\left[\left(\frac{2h}{\beta d}\right)^2 - 1\right]}}. \quad (11)$$

Comparison of the method of this section with

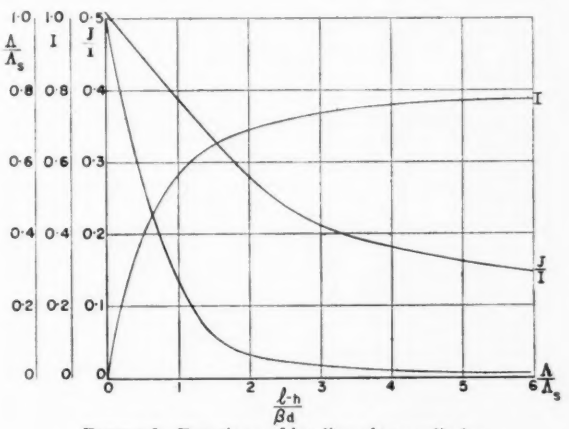

FIGURE 3. Functions of loading along cylinder.

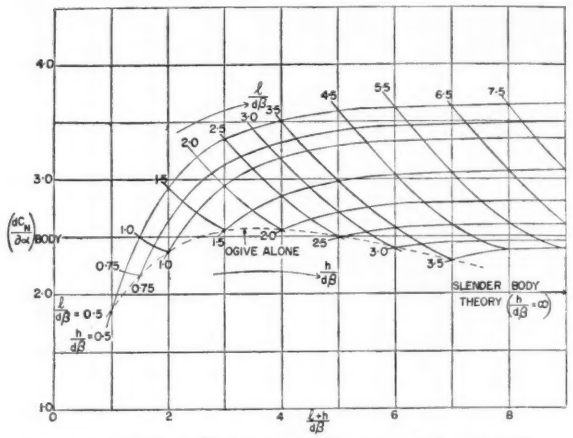

FIGURE 4. Ogive cylinder normal force curve slope ($\alpha=0$).

experimental data shows that it predicts to better than 10 per cent for the normal force slopes and within $\frac{1}{4}$ calibre for the centres of pressure. The agreement with the data of Dennis and Syvertson[11], which may be considered the most accurate available, is twice as good.

2.2. TANGENT-OGIVE-CYLINDERS

Although there exists sufficient data to determine the rate of fall off of local loading along the cylinder of an ogive-cylinder combination, as in the case of the cone-cylinder, for use with a method similar to that of section 2.1 the required data for the flow over ogives at small incidences does not exist. However, it is possible to correlate the available wind tunnel data for normal force slope and centre of pressure at zero incidence using supersonic similarity parameters. The results are shown in Figs. 4 and 5 respectively as functions of $h/\beta d$ and $l/\beta d$.

Comparison of the correlation with the original experimental data shows that it predicts the normal force slopes to 10 per cent and the centres of pressure to within one calibre. The data of Dennis and Syvertson[11] seems to be consistently 5 per cent higher and $\frac{1}{2}$ calibre farther back than that from other sources.

From the very limited experimental data available for bodies with secant-ogive and parabolic forebodies it appears that predictions of adequate accuracy can be made by considering an equivalent tangent-ogive-cylinder.

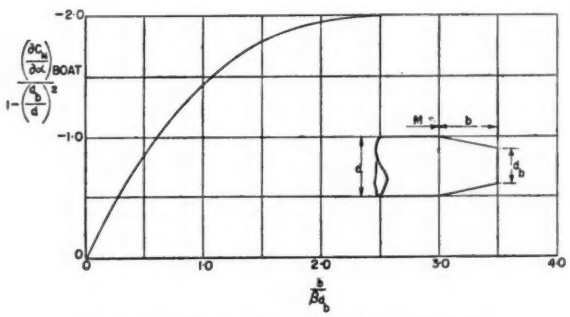

FIGURE 6. Normal force slope due to boat tail.

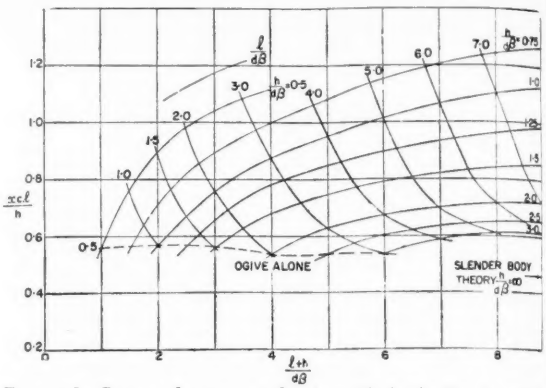

FIGURE 5. Centre of pressure of ogive-cylinder bodies (α small).

2.3. EFFECT OF BOAT-TAILING

The alterations to the normal force slope and centre of pressure at zero incidence due to the boat-tailing of a cylinder extending to a considerable distance upstream have been determined under the restrictions of linearised theory by Zienkiewiez[12]. These are shown in Figs. 6 and 7 respectively as functions of d_b/d and $b/\beta d_b$. The effect of boat-tailing on a body can now be determined by superimposing these results on the characteristics of the body of the same length without a boat tail.

3. Viscous Crossflow Effects

There are at present three commonly used methods of estimating viscous crossflow effects on bodies of revolution at high incidence:—

(1) That due to Allen[5]. The flow over the body was resolved into components perpendicular and parallel to the body axis and the components were assumed independent. The loading due to viscous separation effects was obtained from existing experimental data on the steady flow past a circular cylinder under the conditions given by the crossflow component of the flow over the body. It will be realised that the physical picture associated with this method is incorrect. In general Allen's approach will over-estimate the contributions from the viscous crossflow on the forward parts of the body, under-estimate the contributions in

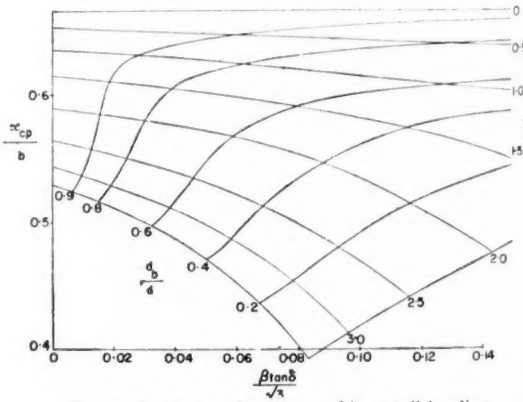

FIGURE 7. Centre of pressure of boat tail loading.

the regions where the main separations are developing but give reasonable values at the rear of very long bodies.

(2) That due to Kelly[6]. The loading due to viscous separation effects was obtained from Schwabe's data[7] on the unsteady flow past a circular cylinder started impulsively from rest. In general Kelly's modification tends to give too slow a build up of viscous crossflow effects along the body and overestimates the loading at the rear of very long bodies.

(3) That due to Küchemann[13]. Küchemann approximated to the real flow pattern around a body at high incidence by replacing the vortex sheets arising from the separations on the lee-side of the body by plane vortex sheets, the direction of the vortex filaments being midway between that of the body and the free-stream. This method is not significantly better than the previous two.

However, the variation of loading due to viscous crossflow effects along a body of revolution at incidence is qualitatively similar to the variation of the drag of a cylinder impulsively started from rest and it would seem plausible to use a variation of the local loading along the body such as that shown in Fig. 8 derived from available experimental data. From pressure distribution measurements on a cone at incidences up to 30°[14] it appears that viscous crossflow effects can be neglected on the cone of a cone-cylinder combination at incidences up to at least 15° and probably could be neglected on the forebody of most bodies with cylindrical afterbodies.

If only the cylindrical afterbody is assumed to be affected by the viscous crossflow then the normal force due to this is given by

$$\Delta C_N = \frac{2}{\pi} \cdot \sin 2\alpha \cdot \Delta I, \quad . \quad . \quad (12)$$

where $$\Delta I = \int_0^{\left(\frac{l-h}{d}\right)\tan\alpha} C_{Dc} \cdot d\left\{\left(\frac{x-h}{d}\right)\tan\alpha\right\} \quad . \quad . \quad (13)$$

and $$\Delta C_M = \frac{4}{\pi} \sec^2\alpha \left[\Delta J + \left(\frac{h}{d}\right) \cdot \tan\alpha \cdot \Delta I\right], \quad (14)$$

about the nose of the body, where

$$\Delta J = \int_0^{\left(\frac{l-h}{d}\right)\tan\alpha} C_{Dc} \cdot \left\{\left(\frac{x-h}{d}\right)\tan\alpha\right\} \cdot d\left\{\left(\frac{x-h}{d}\right)\tan\alpha\right\} \quad (15)$$

ΔI and ΔJ are shown in Fig. 8 as functions of $\frac{l-h}{d}\tan\alpha$.

Therefore the total body alone normal force $C_{N_{BODY}}$ is given by

$$C_{N_{BODY}} = \sin\alpha \left(\frac{\partial C_N}{\partial \alpha}\right)_{BODY} + \Delta C_N \quad . \quad (16)$$

and the pitching moment $C_{M_{BODY}}$ about the nose of the body by

$$C_{M_{BODY}} = \sin\alpha \left(\frac{\partial C_M}{\partial \alpha}\right)_{BODY} + \Delta C_M. \quad . \quad (17)$$

This data for high incidence must be considered speculative although reasonable agreement has been found with the very limited amount of experimental data available. In general the method is as good as Allen's for long afterbodies and as Kelly's for short afterbodies and also provides reasonable estimates within the intermediate range for which neither of these is really applicable.

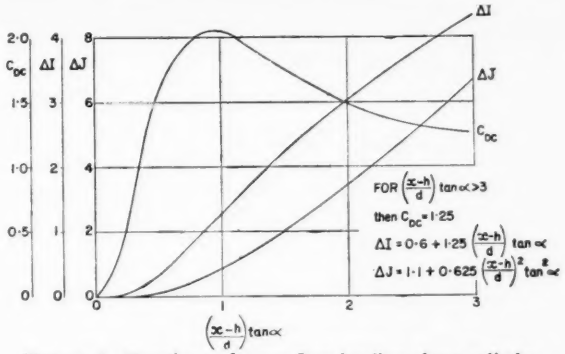

FIGURE 8. Functions of cross flow loading along cylinder.

APPENDIX

PRANDTL-MEYER EXPANSION AT CONE-CYLINDER JUNCTION

It is well known that the flow around a sharp corner in three-dimensional flows is locally two-dimensional. The flow immediately downstream of the shoulder of a cone-cylinder is therefore expressible in terms of the flow quantities tabulated by Kopal[4]. The usual notation[4, 15-17] is used throughout.

NOTATION

M, U	local Mach number and velocity along conical flow generators
p, ρ, T	local pressure, density and temperature respectively
α	incidence
δ	cone semi-angle
η, ξ, μ, x, β	first order perturbation coefficients defined in the text
ϕ	the polar angle measured from the upstream generator in the plane of incidence
γ	specific heat ratio = 1·405
ν	characteristic angle of Prandtl-Meyer flow

Suffixes

c	refers to conditions on the cone
s	refers to conditions immediately behind shoulder
t	refers to stagnation conditions behind nose shock

barred quantities refer to conditions at zero incidence

DEFINITION OF FLOW PROPERTIES ON CONE AT INCIDENCE

To first order in incidence the ratio of flow properties on a cone at incidence to those at zero incidence can be expressed in terms of perturbation coefficients[4, 15], which are a function of cone semi-angle and free stream Mach number only, as follows:—

$$\frac{p_c}{\bar{p}_c} = 1 + \frac{\eta}{\bar{p}_c}\alpha\cos\phi, \qquad \frac{\rho_c}{\bar{\rho}_c} = 1 + \frac{\xi}{\bar{\rho}_c}\alpha\cos\phi,$$

$$\frac{T_c}{\bar{T}_c} = 1 + \frac{\mu}{\bar{T}_c}\alpha\cos\phi, \qquad \frac{U_c}{\bar{U}_c} = 1 + \frac{x}{\bar{U}_c}\alpha\cos\phi,$$

and $$\frac{M_c}{\bar{M}_c} = 1 + \frac{\beta_c}{\bar{M}_c}\alpha\cos\phi.$$

$\frac{\eta}{\bar{p}_c}$, $\frac{\xi}{\bar{\rho}_c}$ and $\frac{x}{\bar{U}_c}$ are tabulated in Ref. 4. Using the perfect

gas law $p=\rho RT$ it can easily be shown that to first order in incidence

$$\frac{\mu}{\overline{T}_c}=\frac{\eta}{\overline{p}_c}-\frac{\xi}{\overline{\rho}_c} \qquad \text{and} \qquad \frac{\beta_c}{\overline{M}_c}=\frac{x}{\overline{U}_c}-\tfrac{1}{2}\left\{\frac{\eta}{\overline{p}_c}-\frac{\xi}{\overline{\rho}_c}\right\}$$

The flow properties on the cone at zero incidence can be obtained from the tables of Ref. 18. The flow properties just behind the shoulder at zero incidence can be obtained from the cone values using the usual Prandtl-Meyer expansion formulae with $\gamma=1{\cdot}405$.

FLOW PROPERTIES IMMEDIATELY BEHIND SHOULDER AT INCIDENCE

The flow turns an angle δ, equal to the cone semi-angle at the shoulder. From the usual Prandtl-Meyer flow equations then

$$\delta=\sqrt{\lambda}\tan^{-1}\sqrt{\left(\frac{M_s^2-1}{\lambda}\right)}-\sqrt{\lambda}\tan^{-1}\sqrt{\left(\frac{M_c^2-1}{\lambda}\right)}-\\-\tan^{-1}\sqrt{(M_s^2-1)}+\tan^{-1}\sqrt{(M_c^2-1)}$$

where $\lambda=\dfrac{\gamma+1}{\gamma-1}$ (for $\gamma=1{\cdot}405$, $\sqrt{\lambda}=2{\cdot}4369$)

Now it is reasonable to assume that the expressions for the ratio of flow values at incidence to those at zero incidence will be similar to those for the flow properties on the nose cone. Thus if

$$\frac{M_s}{\overline{M}_s}=1+\frac{\beta_s}{\overline{M}_s}\alpha\cos\phi$$

then by substituting for M_s and M_c in the equation above and remembering that this equation is also valid at zero incidence one can derive after considerable algebra that

$$\frac{\beta_s}{\overline{M}_s}=\frac{\beta_c}{\overline{M}_c}\left\{\frac{\overline{M}_s^2-1+\lambda}{\overline{M}_c^2-1+\lambda}\right\}\sqrt{\left(\frac{\overline{M}_c^2-1}{\overline{M}_s^2-1}\right)}$$

To obtain the other flow properties account must be taken of the variation of stagnation conditions around the nose cone when at incidence due to the change in position of the cone's shock wave. For example

$$\frac{p_s}{\overline{p}_s}=\frac{p_s}{p_t}\cdot\frac{p_t}{p_c}\cdot\frac{p_c}{\overline{p}_c}\cdot\frac{\overline{p}_c}{\overline{p}_t}\cdot\frac{\overline{p}_t}{\overline{p}_s}$$

Now, as before, $\dfrac{p_0}{\overline{p}_c}=1+\dfrac{\eta}{\overline{p}_c}\alpha\cos\phi,$

from the usual isentropic flow relations

$$\frac{p_t}{p_c}\frac{\overline{p}_c}{\overline{p}_t}=\left[\frac{1+\dfrac{\gamma-1}{2}M_c^2}{1+\dfrac{\gamma-1}{2}\overline{M}_c^2}\right]^{\frac{\gamma}{\gamma-1}},$$

and from the Prandtl-Meyer expansion formulae

$$\frac{p_s}{p_t}\frac{\overline{p}_t}{\overline{p}_s}=\left[\frac{1+\cos\left\{\dfrac{2}{\sqrt{\lambda}}\left(A+\dfrac{\beta_s}{\overline{M}_s}B\alpha\cos\phi\right)\right\}}{1+\cos\left[\dfrac{2A}{\sqrt{\lambda}}\right]}\right]^{\frac{\gamma}{\gamma-1}},$$

where $A=\bar{\nu}_s+\tan^{-1}\sqrt{(\overline{M}_s^2-1)}$

and $B=\dfrac{\lambda\overline{M}_s^2}{(\overline{M}^2-1+\lambda)\sqrt{(\overline{M}_s^2-1)}}$

with $\bar{\nu}_s$ being the characteristic angle corresponding to $\overline{M}_s$. Substituting and expanding to first order in incidence one finally derives that

$$\frac{p_s}{\overline{p}_s}=1+\frac{\eta_s}{\overline{p}_s}\alpha\cos\phi$$

where

$$\frac{\eta_s}{\overline{p}_s}=\frac{\eta}{\overline{p}_c}-\left(\frac{\gamma}{\gamma-1}\right)\frac{\beta_c}{\overline{M}_c}\left\{\frac{2\overline{M}_s^2(\overline{M}_c^2-1)}{(\overline{M}_s^2-1)(\overline{M}_c^2-1+\lambda)}-\frac{(\gamma-1)\overline{M}_c^2}{1+\left(\frac{\gamma-1}{2}\right)\overline{M}_c^2}\right\}$$

Similar expressions can be derived for the density, temperature and velocity ratios.

LOCAL LOADING IMMEDIATELY BEHIND SHOULDER AT INCIDENCE

The local loading is obtained by a suitable integration of the local pressures around the cylinder and gives immediately behind the shoulder that

$$\left(\frac{\partial C_N}{\partial\alpha}\right)_{\text{LOCAL}}=\frac{1}{\gamma M_1^2}\frac{\eta_s}{\overline{p}_s}\frac{\overline{p}_s}{p_1}$$

where subscript 1 refers to free stream conditions.

Flow conditions downstream of the shoulder could be determined as a power series in distance from the shoulder using the technique suggested by Johannsen and Meyer[19].

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TECHNICAL NOTES

Prediction of Transition in the Boundary Layer on an Aerofoil

by
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TRANSITION to turbulence in the boundary layer on an aerofoil may occur in several different ways, not the least important of which is by bubble separation of the laminar layer. Thus in establishing an empirical criterion for the limit of existence of a laminar boundary layer the necessary parameters must be able to describe separation and instability, as well as being physically reasonable and simple to calculate and use.

It is shown that only two parameters are necessary to fulfil these conditions, and that a universal curve may be constructed of boundary layer Reynolds number R_{δ_2} against pressure gradient parameter m at transition. This curve may be used to predict transition, and an assessment of its accuracy in comparison with previous methods is given.

Theoretically the method can be extended to the limited case of bodies of revolution at zero incidence.

INTRODUCTION

The actual mechanism of transition to turbulence in a boundary layer is not known, although recently much progress has been made. It is therefore impossible to calculate conditions in the transition region, let alone find the values of parameters such as H (ratio of displacement and momentum thicknesses) at the beginning of the fully-developed turbulent boundary layer. This is one of the main gaps in methods of predicting aerofoil characteristics. For small incidences (low values of C_L) it appears to be sufficient to assume $H = 1{\cdot}4$ as the initial value in calculations of the development of the turbulent boundary layer. The location of transition still requires to be known however. Transition is often due to laminar separation when a bubble is formed and reattachment as a turbulent boundary layer follows the turbulent mixing process at the rear of the bubble. Thus care is needed in applying some of the methods of predicting transition which have been proposed from time to time, since these take account only of transition due to Tollmien-Schlichting instability.

NOTATION

c aerofoil chord
t aerofoil thickness
s distance along aerofoil surface
z distance normal to aerofoil surface
δ_1 displacement thickness
δ_2 momentum thickness
$H = \delta_1/\delta_2$
U_0 velocity of main flow
U velocity at the edge of the boundary layer
u velocity in the boundary layer

$$U' = \frac{\partial U}{\partial s}$$

$$R = \frac{U_0 c}{\nu}$$

$$R_{\delta_2} = \frac{U\delta_2}{\nu}$$

$$R_s = \frac{Us}{\nu}$$

$$m = -\frac{U'\delta_2^2}{\nu}$$

α angle of incidence
C_L lift coefficient

Suffix

T transition

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A CRITERION FOR TRANSITION

We shall not attempt to explain transition, but rather try to establish an empirical criterion for where transition may be expected, *i.e.* to determine how long a laminar layer may be able to exist. Thus the boundary layer

(*a*) must not separate,
and (*b*) must be stable.

To establish such a criterion for transition we wish to use parameters which are

(*i*) physically reasonable and not too arbitrary,
(*ii*) suitable for describing both separation and Tollmien-Schlichting instability.
(*iii*) simple to calculate and use.

Thwaites' method[1] (with modifications proposed by Curle and Skan[2]) provides the criterion for separation, which is predicted to occur when the pressure gradient parameter $m = -\frac{U'\delta_2^2}{\nu}$ reaches the value 0·090. Here δ_2 is the momentum thickness and U is the velocity at the edge of the boundary layer, the prime denoting differentiation with respect to distance along the wall.

Tollmien-Schlichting instability, as treated by Lin[3] for example, may also be described by this same parameter. Lin's theory predicts a minimum critical Reynolds number (for a given pressure gradient) below which infinitesimal disturbances are damped out. Above this critical Reynolds number disturbances of certain wave lengths may be selectively amplified and this has been proposed as part of the mechanism of transition. Calculations have shown that there is a universal curve of boundary layer Reynolds number $\frac{U\delta_2}{\nu} = R_{\delta_2}$ for the onset of instability against the pressure gradient parameter m, and Granville[4] has reproduced such a curve. Other parameters appear to serve equally well, for instance, Pretsch[5] uses

$$T = \frac{\delta_1}{U}\left(\frac{\partial u}{\partial z}\right)_{z=0},$$

and also $H = \frac{\delta_1}{\delta_2}$ could be used. Thwaites' universal curves of H and $l = \frac{\delta_2}{U}\left(\frac{\partial u}{\partial z}\right)_{z=0}$ against m reconcile the use of these different parameters.

A universal critical Reynolds number curve has also been presented by Chiarulli and Freeman[6], but all these curves agree when converted to the same parameter.

Now fully developed turbulence first appears in the boundary layer some distance downstream of the limit of

stability, and Pretsch[5] has shown that the amount of amplification in the region of instability of the laminar layer depends to a large extent on the pressure gradient parameter. This prompted Granville[4] to propose a universal curve of average Reynolds number over the unstable region against the average pressure gradient in the same region. Analysis of some experimental data confirmed this idea, but the experimental information available was rather meagre. To go one step further it seems reasonable that an empirical criterion for transition may be obtained by plotting the boundary layer Reynolds number at transition, $(R_{\delta_2})_T$, against the pressure gradient parameter $(m)_T$.

To sum up, for the purpose of predicting transition, it appears that two parameters may be sufficient and that these may produce a universal curve. R_{δ_2} plotted against m at transition is such a pair. For transition caused by laminar separation the required parameter is m alone.

The quantities R_{δ_2} and m have been calculated at the observed transition position on various aerofoil sections from a fair number of tests. The results are plotted in Fig. 1 and it will be seen that a universal curve can indeed be drawn through the experimental points.

To use this curve for predicting the transition position (more strictly, the limit of existence of the laminar layer) it is only necessary to calculate the boundary layer development and to plot R_{δ_2} against m on Fig. 1. The intersection with the universal curve gives the estimated transition conditions.

However, since we have treated the simpler problem of the ability of a laminar boundary layer to exist, the predicted position may not actually be the place where a fully turbulent layer can be observed. In some cases the prediction may be very good, for instance, when there is a short bubble. In other cases the accuracy may be much less as, for example, when intermediate modes occur (as described by Stuart[7]) and take time to supersede one another, or when there is a long bubble.

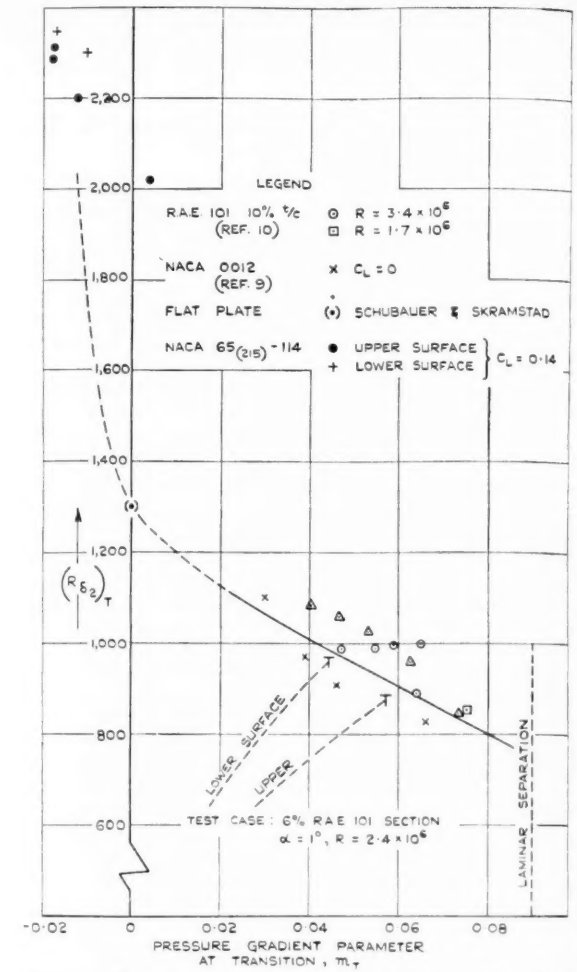

FIGURE 1. Boundary layer Reynolds number at transition plotted against the pressure gradient parameter.

COMPARISON WITH OTHER METHODS

In Granville's method it is first necessary to determine the limit of stability from the universal curve of $R_{\delta_2} \sim m$. A process of iteration using a curve of average R_{δ_2} against average m over the unstable region then yields the transition position. In view of the extra complication this method will not be discussed further.

A method proposed by Michel[8] depends on a universal curve of $R_{\delta_2}=\frac{U\delta_2}{\nu}$ at transition against $R_s=\frac{Us}{\nu}$ at transition, where s is distance measured along the aerofoil surface. The calculated curve of $R_{\delta_2} \sim R_s$ for a given case then intersects the universal curve at the (predicted) transition position. Examples of the use of this method are shown in Fig. 2. Curves (*a*) and (*b*) were calculated for a N.A.C.A. 0012 section at $C_L=0$ using the theoretical pressure distribution, the Reynolds numbers of $2{\cdot}2\times10^6$ and $7{\cdot}2\times10^6$ being those of tests by von Doenhoff[9]. Calculated conditions at the measured transition position are indicated by the symbol T. Michel's curve predicts transition points which are in error by 10 per cent of the chord for $R=2{\cdot}2\times10^6$, but by only 3 per cent for $R=7{\cdot}2\times10^6$. It is possible that more consistent results would be obtained by using measured pressure distributions for calculating the laminar boundary layer development, but these are not always available. Curve (*c*) was calculated for the upper surface of an R.A.E. 101 section at $C_L=0{\cdot}1$, and the Reynolds number of $3{\cdot}4\times10^6$ corresponds to tests by Brebner and Bagley[10]. Here the predicted transition position is again in error by about 10 per cent of the chord.

Curves such as (*a*), (*b*) and (*c*) in Fig. 2 intersect Michel's universal curve at quite an acute angle so that large errors in predicted transition positions may easily arise. However, Smith[11] has independently explained the theoretical basis of the choice of parameters in Michel's method. He also concludes that Michel's method gives good results in two-dimensional cases provided the velocity distribution is similar to one or more of those used in constructing the universal curve. One case analysed in detail by Smith was a N.A.C.A. body of revolution of fineness ratio 9 at zero incidence. Applying Mangler's transformation it is possible to extend Michel's correlation method to include such axi-symmetric flows, but Smith found that the results had only a low degree of accuracy.

The new method using the universal curve of Fig. 1 also gives poor accuracy in this case. The universal curve is not too well established in the region where $m<0{\cdot}04$ due to the scarcity of experimental points in regions of low pressure gradients. In any case accuracy is expected to be highest where $m>0{\cdot}04$ for then, due to the steeper

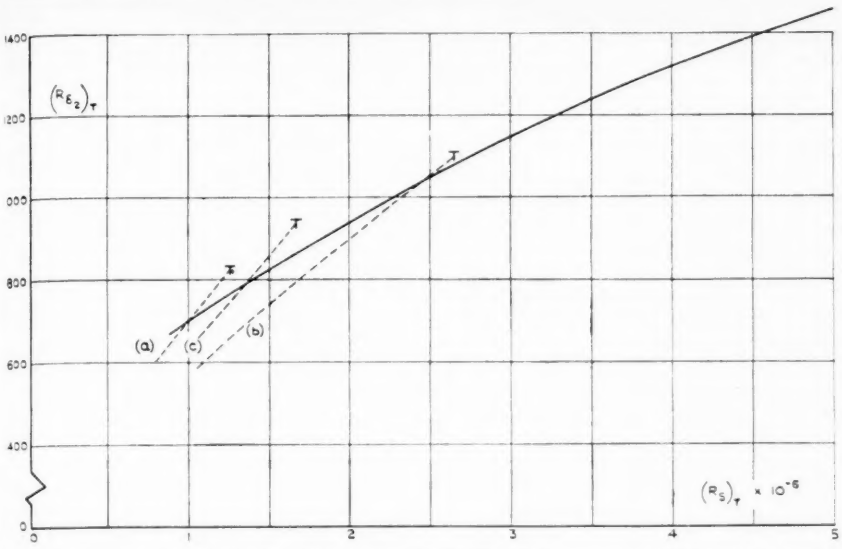

FIGURE 2. Michel's universal curve for predicting transition (Ref. 8).

adverse pressure gradients, the value of m changes quite rapidly with distance along the surface.

As a test the laminar boundary layer development on both surfaces of an R.A.E. 101 6 per cent t/c section has been calculated for an experimental pressure distribution obtained at an incidence of one degree and $R = 2{\cdot}4 \times 10^6$. Conditions at the measured transition positions are indicated on Fig. 1 by symbol T. In both cases the error in the predicted position is only about 2 per cent of the chord, *i.e.* hardly greater than the estimated experimental error in measuring transition location by the evaporation technique used in this particular test.

A useful criterion which emerges from the universal curve of Fig. 1 is that for determining whether transition precedes laminar separation. This is particularly important in relation to the question of leading-edge bubble formation on thin aerofoils at incidence. The criterion is that if R_{δ_2} at the theoretical separation point is greater than about 750, then transition may be expected to have occurred first and thus a bubble will not be formed.

Hama[13] remarked that " local separation does not necessarily lead to immediate transition." In many practical cases, however, laminar separation of the short bubble type is in fact the cause of transition, and many wind tunnel transition experiments that were analysed with a view to including the results in Fig. 1 were found to be of this class. The importance of a short bubble separation as an agency for provoking transition must be strongly emphasised therefore. In general, though, what happens after a laminar separation must be left an open question and in this connection investigations of the stability of separated shear layers would be particularly valuable.

More work remains to be done on the question of free-stream turbulence to which transition is very sensitive. All the wind-tunnel tests analysed to yield the universal curve of Fig. 1 were for low levels of free-stream turbulence (0·1 to 0·2 per cent) since this is more representative of flight conditions. Strictly speaking, separate curves should be drawn for different levels of turbulence, but for most practical purposes the single curve presented here should be adequate. Similar remarks apply to the question of roughness of the aerofoil surface.

CONCLUSION

The ability of a laminar boundary layer to exist has been considered, and in particular the questions of separation and of instability of the laminar layer. Two parameters only appear to be sufficient to describe both of these phenomena, and a universal curve of boundary layer Reynolds number based on momentum thickness R_{δ_2} against pressure gradient parameter m at transition is presented.

From this curve it is concluded that if R_{δ_2} at the theoretical laminar separation point (given by $m = 0{\cdot}090$) is greater than about 750 then transition may be expected to have occurred first.

More data are required for the region of the curve relating to low pressure gradients (up to about $m = 0{\cdot}04$) but the curve can be used with some confidence in regions of higher adverse pressure gradients.

If separation precedes transition the separation point, $m = 0{\cdot}090$, is a good approximation to transition only if a short bubble is formed. If a long bubble is formed then transition may be some way downstream of the separation point (*see* Ref. 12).

Theoretically the method of predicting transition can be applied to bodies of revolution by using Mangler's transformation. However, only the case of zero incidence can be treated, and then the pressure gradients are usually so low as to be in the doubtful part of the universal curve of $(R_{\delta_2})_T \sim m_T$.

An extension of the present method to swept-back wings appears to be doubtful. In any event it would only apply to regions where infinite sheared-wing conditions are approximately realised. Transition due to instability of the secondary flow is another complicating factor in such cases.

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A Tensile Strut Testing Machine

by

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SLENDER STRUTS are usually tested with pin joints at both ends, because this is the theoretical condition which is most readily achieved (or closely approximated to) in practice. In conventional testing machines this results in a compression column with two pin joints. The instability of this column makes the accurate alignment of the loading members important, and reliable testing becomes correspondingly difficult.

The proposed machine avoids these difficulties because the loading members are in tension. Fig. 1 shows the simple arrangement of four equal pin jointed links *AB*, *BC*, *CD*, *DA*. *AC* represents the strut to be tested, which is compressed when a tensile force *P* is applied at *B* and *D*. Each tension link consists of two equal bars placed symmetrically relative to the vertical plane containing the forces *P* and the axis of the strut; this reduces the stresses in the hinge pins. The weights W_1 and W_2 are connected to *BC* and *AB* respectively and adjusted to balance the weight of the links so that the frame without the test strut is in neutral equilibrium. This facilitates loading and avoids the need to allow for the weight of the apparatus when the force *P* is applied as a dead weight. Alternately the machine may be loaded in a tensile testing machine.

If the forces in the links are *Q* units and the force applied to the strut is *R*, from a funicular polygon of forces

$$R = P \cot \alpha \text{ and } Q = \tfrac{1}{2} P \operatorname{cosec} \alpha \qquad (1)$$

This assumes frictionless pin joints. If the four hinge pins are of radius *r* and if these pins are arranged not to rotate relative to the strut, assuming a coefficient of friction μ between the pins and the links, the effect of friction may be considered as follows.

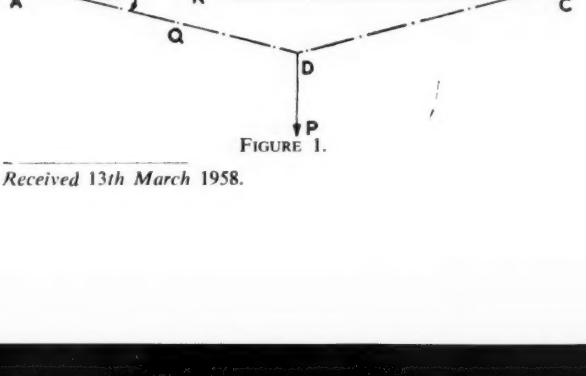

FIGURE 1.

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Figure 2 shows the forces acting on a link.

By taking moments about *C*,

$$Pl \cos \alpha = 2Ql \sin \alpha \cos \alpha + \mu Q (l + r) + \mu Qr$$

and from moments about *D*,

$$Rl \sin \alpha = 2Ql \sin \alpha \cos \alpha - \mu Q (l + r) - \mu Qr$$

Hence

$$R = \frac{1 - \mu \left[\dfrac{1 + 2r/l}{\sin 2\alpha} \right]}{1 + \mu \left[\dfrac{1 + 2r/l}{\sin 2\alpha} \right]} \times P \cot \alpha$$

It may be assumed that $2r/l$ is small compared to one for any practicable design, but the effect of friction increases with decreasing values of α. It is therefore essential that the coefficient of friction at the hinges be kept as low as possible and roller bearings would appear suitable.

Because *R* depends on α it is necessary to measure the distance $BD = 2y$, say. In terms of this measured distance and the known link length *l*

$$R = \frac{[1 - (y/l)^2]^{\frac{1}{2}} - \dfrac{\mu}{2}\left(\dfrac{l}{y} + \dfrac{2r}{y}\right)}{\dfrac{y}{l} + \dfrac{\mu (1 + 2r/l)}{2[1 - (y/l)^2]^{\frac{1}{2}}}} \times P$$

$$\simeq [(l/y)^2 - 1]^{\frac{1}{2}} P$$

if the effect of friction is neglected. The measurement of the distance $2y$ is not difficult because direct reading from a steel rule should be sufficiently accurate for all but very small struts.

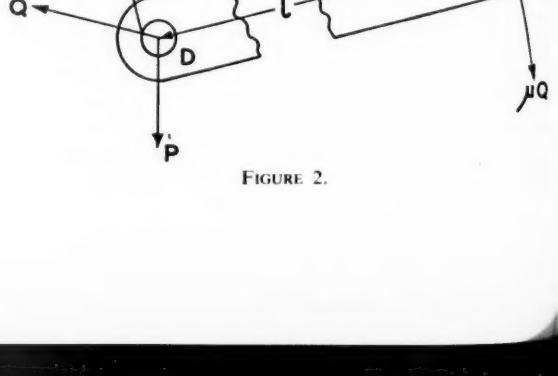

FIGURE 2.

The Millionth Chance

by

HUGH OSWALD SHORT, Hon.F.R.Ae.S.

IN THE December 1957 Journal there was a review of "The Millionth Chance" by James Leasor (p. 843). The disaster to the rigid Airship R.101, was not a "millionth chance" to me, it was a foregone conclusion.

With a loan from the Admiralty, I planned and built Cardington Airship Works, to the west of it now stands Shortstown, a postal address. The Admiralty designers were responsible for the design of all airships built there, during the time it was controlled by Short Brothers, all except the design of the gas compartments. The gas compartments were made according to my instructions. They were made of rubberised fabric, two layers of cotton and two layers of rubber, one layer between the fabric and one layer on the inside of the bags.

On this inside rubber, we laid three thicknesses of Oxgut, or as it is sometimes named, Gold Beaters skin. When prepared for use they are beautiful white skins, extremely thin, and they do not smell when dry. They only smell if allowed, when washed in water, to go bad in hot weather. Mr. James Leasor refers to "Damp stinking covers laced with the guts of bullocks." If there was any smell it would be from impure hydrogen. It is not an unpleasant smell to me, but hydrogen not properly purified could have been made in the Hydrogen Plant at Cardington, especially if the process of making the gas was hurried. Pure hydrogen has no smell whatever, and therein lies the danger of being gassed.

After the First World War I was called to a Board Meeting of the Admiralty. Sir Vincent Raven was in the Chair, and I was given a seat on his left. He told me that the Government proposed to Nationalise Cardington Airship Works. I protested, saying it would be breaking the agreement between the Admiralty and Short Brothers.

Sir Vincent replied that the Government could break any Agreement under the Defence of the Realm Act, and that all I could do was to claim compensation. No other member of the Board spoke on that occasion. The conversation was only between Sir Vincent Raven and myself. I was directed to another office in Whitehall, where I agreed to accept £40,000 compensation on behalf of Short Brothers. So Cardington Airship Works was nationalised.

Later, the Airship Guarantee Company made an offer to purchase Cardington Airship Works. The terms of that offer to purchase were debated in Parliament and reported in Hansard. Apparently the offer was nearly accepted, but Lord Thompson wanted to retain the works. The day before the final decision was to be made, I was visited by General Brooke-Popham, when I was having breakfast at my house in Rochester. He said that Lord Thompson wanted to keep Cardington Airship Works nationalised, but was afraid that they would have no experienced men to staff the Airship Works. I was asked if all the staff Short Brothers had employed could be returned to Cardington, and I agreed. Cardington Airship Works remained nationalised, but I received no request for any of our men.

When R.101 was nearing completion I was invited to go and see it, as were German Airship Constructors. The rigid framework of the ship was made of steel tubing and it was certainly a sound engineering job. The Germans were also impressed by this rigid framework, and said it was superior to any German Airship previously built.

I then went into the shop where girls were making the gas compartments. To my surprise, they were covering single sheets of linen with one thickness of Oxgut. I asked one young woman if she was sure she could make the fabric gas-tight. She replied, "Yes, all the skins are examined by microscope." When I asked to see the microscope, she handed me a reading glass. Of course not even the Electron Microscope would show a hole through which hydrogen could escape. Even with two layers of cotton and two layers of rubber and three thicknesses of Oxgut, hydrogen would escape, but very slowly.

It is certain that the disaster was caused by the rapid leakage of hydrogen. I was told later that before the ship left land when it was at the mooring mast, the gas compartments required an additional charge of hydrogen.

In Mr. James Leasor's account of the disaster taken from the few men who escaped, it is stated, "The Gigantic Gas Bags moved continually like living things as the *air pressure changed*. Now they would be huge balloons, glowing with a faint eerie luminosity in the dim height of the arched roof, so that a man could walk beneath them and see them suspended above *like enormous pears*. Then a change in pressure would bring them down, flabby and bloated, so that he had to thrust his way past them.

No doubt that is how matters would appear to men in such a desperate experience, but the fact that the gas bags appeared "pear shaped" shows that a great quantity of gas had escaped. The fabric would be surging about, so that the man would have at times to push his way past it, but no "change of pressure" would bring them down "flabby and bloated." The terms "flabby and bloated" are contradictory. The men were engineers, and they do understand the necessity of keeping the engines going for the following reason:— As the gas escaped, an attempt would be made by the Captain to depress the stern of the Airship by the tail elevators, so causing the airship to climb like a kite. This was always done to cause an airship either to rise or descend without losing ballast or valving to lose gas. Both gas and ballast a Captain seeks to preserve, and valving or letting ballast go is done only for special reasons, or in an emergency.

It is clear that the tail elevators, in an attempt to "Kite" the Airship were in the fully elevated position, and the stern could no longer be depressed. That seems to be proved by the statement, "I'm glad you got that aft engine running all right" (he said), "That could have held us up a lot."

The day of airships filled with hydrogen is gone forever. The non-rigid airships now made and used in the U.S.A. and inflated with non-inflammable Helium were useful in the Second World War, and would be in any future war for protecting convoys of merchant ships.

Guided Flight Section

MR. P. A. T. CHRISTOPHER'S timely note (May JOURNAL, p. 388) regarding the future work of the Guided Flight Section raises some difficult issues. It is noteworthy that of the first six lectures given, only one has been by a member of the Society. As he remarks, it is imperative that free discussion on detailed engineering aspects should take place on any future lectures given to the Guided Flight Section, if they are to be really worthwhile. To do this may mean that certain sessions would have to be held *in camera* with appropriate security clearance being obtained. It is to be hoped that any future programme will cover not only problems in electronic, hydraulic, pneumatic, aerodynamic and structural techniques and methods of construction and quality control, but also the wider issues of engineering management, co-ordination, administration, education, training, facilities and finance, and so on. The field covered by the art and science of guided flight is extremely large and this may well necessitate having two or three lectures devoted to certain aspects of the work. Every effort should be made to make this new section of the Society a meeting place for the dissemination of technical knowledge which may ultimately be used in other branches of engineering.

B. T. TURNER, A.F.R.Ae.S., *English Electric Co. Ltd.*

Graduates' and Students' Section

The Visit to B.O.A.C. at London Airport

On the afternoon of Saturday 31st May, we visited B.O.A.C. at London Airport. Despite the London bus strike, most of the party managed to get there.

B.O.A.C. have a very well organised system of tours and visits to the airport. Our guide, Mr. Vere, was able to quote from memory all the statistics regarding B.O.A.C. and London Airport; it is Europe's busiest airport, B.O.A.C. shares it with 37 other airlines, 26,000 people work there, 300 tanker lorries are needed each day to bring in the fuel for the aircraft, and so on. After telling us this in the briefing room, he led our assorted fleet of cars to the B.O.A.C. Headquarters and Maintenance Base.

This enormous building, familiar to people using the road from Hounslow to Staines, comprises four large hangars in which major overhauls can be undertaken. The novel architecture arises from designing for unobstructed entrances 300 ft. wide to each hangar with Brabazon-size aircraft in mind. The wide span is achieved by cantilevering the roof beams from each end pylon, and counterbalancing these with a rather less aesthetic-looking rectangular block of concrete weighing 1,000 tons. Space in between the four hangars is occupied by extensive workshops for the overhaul of components and blocks of offices for administration, making one large building.

Two of the hangars contained Boeing Stratocruisers, and there was an impressive line-up of them outside. The "Strat" is still probably B.O.A.C.'s most popular aircraft among passengers, being relatively spacious, and with the lounge-bar on the lower deck. Next year, they will start to be replaced by the Comet 4, and they have already been succeeded on the North Atlantic run by the long range Britannias.

In another hangar, we saw a Douglas DC-7C. There were only a few of these about, because they are working hard on the non-stop route to New York. The Seven Seas appeared less massively built compared with the other types, being a sure sign of a thoroughly developed aircraft, and essential for a type operating the very longest stages.

Elsewhere, we saw examples of the Britannia 102 and 312, now working well and, inside a 312, we were able to compare directly first class, tourist and economy seating arrangements. The next class after economy would have to be "sardine"! Seeing aircraft at the factory, usually one sees only first class seating, if seats have been fitted.

Thus passed a good, interesting visit, with a cordial invitation to go again in about eighteen months' time when B.O.A.C. have got their Comet 4's and Boeing 707's. N.K.B.

Visit—The de Havilland Aircraft Company

There will be a visit to de Havilland's at Hatfield on the morning of Saturday 23rd August, where we shall see the Comet 4's. Would those interested please write to the Hon. Visits Secretary, Mr. N. K. Benson, 14 Wakering Road, Barking, Essex.

Summer Party

The Section held their Annual Summer Party on 13th June in the offices of the Society. The President, Sir Arnold Hall, visited us during the evening and saw the 150 members and friends enjoying themselves to the music of Arthur Young's Trio. The marathon effort of the evening was reached when the climax to an elimination dance was for the half dozen surviving couples to make a line of their personal belongings. Soon the library was strewn with clothes and personal belongings laid out in line astern. The triumphant couple gained the verdict by half a string of beads.

Grateful thanks must go to the house staff of the Society and the wives and girl friends of the Committee who did valiant work in preparing piles of sandwiches.

Wine and beer were provided and helped to keep the party going even through the rigours of the "Gay Gordons" on a summer's evening. W.E.C.

Local Graduates' and Students' Sections

In response to our request in the May JOURNAL we have received a letter from the Liverpool area, an extract of which is now given:

"The only Section in this vicinity, to my knowledge, is Manchester—forty miles distant. Recently I made official enquiries around Merseyside as to the possible formation of a Branch in Liverpool. Unfortunately the support was very poor and it looks as if a Graduate and Student Section at Liverpool would not be possible. Chester might be an opening because this excellent Branch—now aged eight—has a strong following from we 'young brains'" (Signed W. MCCAFFREY)

Mr. McCaffrey has also kindly offered to help in the formation of a Section and we invite any members living in either the Chester or Liverpool areas to contact him so that we can see what support there might be. The Committee will help in any way they can to assist local Graduates and Students to get together.

Mr. McCaffrey's address is 88 Bidstone Avenue, Claughton, Birkenhead.

THE LIBRARY

Reviews

FLUID-DYNAMIC DRAG. *Dr. S. F. Hoerner. Published by the author, 1958. 400 pp. Illustrated. 15 dollars.*

When Dr. Hoerner wrote his book "Aerodynamic Drag" in 1947 it appeared that the subject matter was too specialised for the liking of the American publishers. As a result it was printed in typescript by a photographic method and published by the author himself. The presentation within one cover of so much collected information on drag was very useful and the book was well received.

The time has now come for a revised version. Dr. Hoerner has changed the title to Fluid-Dynamic Drag in order to remind his readers that these results apply to water as well as to air. He has added much new material and has extended the range of topics even more widely.

The most noticeable change, however, is in format and type. After the success of the first book it would not have been surprising to have found the new edition issued by a well-known publishing house, but the book is again published privately by the author and can be obtained only "by direct mail order" to Dr. Hoerner in New Jersey. A 50 cent discount is offered for cash or bulk orders. Clearly Dr. Hoerner is a believer in individual enterprise.

The touch of a professional publisher is, however, noticeably missing in the printing. The original page size has doubled, the paper is now glossy art throughout and the typescript founts have given way to a conventional type face, but it appears that the un-named printer had no small type suitable for sub-scripts or indices and no Greek letters. Many symbols in the equations appear to have been handwritten on to the proofs which were then printed photographically. This is no great disadvantage if the drawing is done carefully, but some of the symbols, especially the ugly ρ, are irritating in an expensive text. Nevertheless, the high quality paper has enabled the fine detail of the 600 illustrations to be completely readable.

The author sets out to tell all about drag. Enough theory is given to provide the frame on which experimental results are displayed. The bibliographical references, now two thousand of them, came mainly from the U.S.A. and Germany, but other sources are not neglected. The chapter titles include skin friction drag, pressure drag, wind forces on structures (this refers to natural winds), surface irregularities, streamline shapes, drag due to lift, interference drag, internal flow systems, hydrodynamic drag (including cavitating flow), water-borne craft, land-borne vehicles, aircraft components, complete aircraft, influence of compressibility, at transonic and supersonic speeds and drag at high speeds affected by viscosity and rarefaction.

Each chapter begins with the theory and usually includes valuable references (in footnotes) to fundamental papers and books on the subject. Then follow excellent diagrams, tables and curves giving the known experimental measurements. The subject matter is so vast that the reader can best assess the book by reading the sections on which he is most knowledgeable. The first impression is that little has escaped Dr. Hoerner, but it is perhaps a fault to try to include everything. The drag characteristics of birds and of rotary winged aircraft are together disposed of within a page—it would have been better to have omitted these topics rather than to mention them so briefly. Later, when the drag of earth satellites is being discussed, it is rather surprising to find a formula (wrongly given) for the escape velocity from the earth.

One topic which does not appear is the fascinating story of the "swing" of a cricket ball. The effect of Reynolds number on the transition point on a sphere is dealt with, but obviously Dr. Hoerner has never played cricket. He does, however, mention lift on rotating spheres and comments on curved flight path of a ping-pong ball. Surprisingly he adds that golf balls ". . . are comparatively heavy so that any aerodynamic lift that might develop can have only little effect upon their flight through the air." Many aerodynamicist-golfers know better.

The information given on sailplanes is disappointing. The measurements quoted are 25 years old and unrepresentative of modern practice. Present day sailplanes with laminar sections have lift-drag ratios of around 40 and are the most efficient aircraft now flying.

Most of the information in the book concerns aircraft of some kind, but there are excellent chapters on boat resistance and on the drag of cars, trains and bicycles.

Anyone needing to calculate the drag of any new device or system would be well advised to consult this book first. In all probability the work has already been done and, if it has, Hoerner will have the results tabulated and plotted.—A. H. YATES.

SCIENCE NEWS No. 48 (Rocket and Satellite Research Number). *Edited by Archie and Nan Clow. Penguin Books, London, 1958. 142 pp. Illustrated. 2s. 6d.*

When the Atomic Age burst over Japan and a startled world in the summer of 1945, the Penguin people distinguished themselves by quickly producing an excellent little volume explaining the facts of nuclear fission to all those non-specialist readers who realised that this, undoubtedly, was a thing of which they ought to have some understanding. Now that astronautics has come upon the scene in somewhat similar fashion, the publishers have attempted to perform a like service for this subject. Although they have perhaps not succeeded in achieving quite such an outstanding effort this time, they have done extremely well.

Professor Massey of University College, London, and Dr. Boyd, who is one of his staff lecturers, each contribute two chapters. These cover the whole field of physical phenomena in the upper atmosphere and beyond, satellite orbits, and rocket instrumentation—fields in which these two authors, of course, might fairly be described as Britain's leading experts. Squadron Leader Howard of the R.A.F. Institute of Aviation Medicine deals with medical aspects of manned space-flight, while Mr. Stephens and Mr. Lines of the R.A.E. contribute a chapter on guidance and control which is all the more welcome because it is one of the very few authoritative unclassified discussions to have appeared on this important subject. K. W. Gatland of the British Interplanetary Society writes on high-performance rocket vehicles and their progressive development over, in particular, the past twenty years. The chapter on rocket propulsion is by Wilfrid Neat, Chief Engineer of de Havilland's Rocket Division.

The level of the book is just right for the non-specialist technical reader, the undergraduate or the member of the Science Sixth with a thirst for knowledge in this exciting new field. With the above list of authors, the basic accuracy of the work is assured. There are however, one or two signs of hurried preparation which might be corrected in any future printings, *e.g.* a few ambiguities of phrasing in Neat's chapter, and the description of specific

impulse as specific consumption. In Gatland's, there is some confusion about a Russian 1,300 (3,000?) km. missile whose range in miles is said to be 1,865, and in Howard's (though the context correctly indicates the opposite) orbital velocity is stated to be $\sqrt{2}$ times escape velocity. There is a confusing entry for Titan's thrust in the final table, and Fig. 13 shows an actual Jupiter, not the Jupiter C test vehicle. Again, the Soviet rockets in Fig. 14 are definitely not inter-continental types, and it is doubful whether Tass ever claimed that these particular ones were.

However, slips such as these do not really detract to any serious extent from a book which is timely and good value —in fact, worth more than most books on the same subject at five to ten times the price.—A. V. CLEAVER.

THEY FOUGHT FOR THE SKY. *Quentin Reynolds. Cassell, 1958. 304 pp. Illustrated. 21s.*

Quentin Reynolds has collected the memories of the fighter pilots' war in the air during 1914-18 from many (but by no means all) available records and persons, and has presented his condensation of this data in vivid language. He claims his book to be the first international account of that epoch, but the absence of Italian, Russian and Turkish pilots confines that claim to the British, French, German and Americans' participation.

Younger generations, currently gorged with ample helpings of books about the Second World War, may be surprised to discover that 25 years previously preprototype fighter pilots evolved the technique of air fighting from nothing but bitter experience, flying without parachutes, dinghies, Mae Wests, bullet-proof windscreens, armour-plate, self-sealing tanks, oxygen, R/T and all the other advantages of the developments of the Second World War.

But those who flew as pilots in the First World War will notice some gaps in Reynolds' gallery of names, and some inaccuracies in his statements. When enumerating his many sources of information the author surprisingly omits the Air Ministry, the R.Ae.S., and the R.Ae.C., but gives a big hand to two hobbyists who were too young to have served in the 1914-18 War. Perhaps some of his errors of fact stem from these omissions.

Reynolds says 37 British pilots flew to France with the B.E.F. in August 1914. Brancker, who was at Dover airfield, counted 44. Perhaps Reynolds forgot the Aircraft Park aircraft; certainly he does not mention the A.P. He says that most of those pilots were dead within a year and that only two now survive. I know of 20 who survived that war, eight of whom were still alive when Reynolds wrote his book. His dates of landings and departures do not agree with Sir Walter Rayleigh's official history. He gives the command of No. 3 Squadron to Geoffrey Salmond instead of Jack. The Avros were 2-seaters; Maurice Farman nacelles were not perched on the lower wing.

Kitchener did take aeroplanes seriously. His foresight was clear. He refused to allow General Henderson's transfer from the R.F.C., said he intended to have a lot of generals in that Corps, and he doubled the Military Aeronautics Directorate's estimate of aircraft required.

Oliver Swann, not Horace Short, produced England's first seaplane, an Avro with floats. The Constantinesco gun interrupter gear was not rushed into the Allied war in 1915 soon after the Fokker E.IV monoplane appeared. Reynolds' description of early flying on page 34 will amuse old-time pilots by its psychiatrical exaggerations. Reynolds avers that "a one-hour inhalation of [the castor oil fumes from rotary engines] has the same effect upon the human system as would a direct dosage of three or four spoonsful of the stuff." I assure Mr. Reynolds that I flew hundreds of hours behind rotaries from 50 h.p. Gnomes to 230 h.p. Bentleys lubricated with castor oil, and what he writes is just not true; someone has been pulling his leg.

One of Mr. Reynolds' Bleriot monoplanes "used wing warping instead of loose ailerons," but elsewhere we read about "ailerons of the warp control type."

His figures of fighter scores in the British air services are open to question—too few with ten or more victories, too many with 50 or more. He gets personal names wrong —I noticed Lawrence for Loraine, Pemberton-Billings for Pemberton Billing, Sowery for Sowrey, McLoren for McLaren. He has got the story of which Service operated Sopwith Triplanes, and why, mixed up.

Most of his readers will not recognise these mistakes, and it will be unfortunate if they become established and accepted as facts. But in his narratives of the actual air fighting Mr. Reynolds' descriptive powers find wings and few will question that he has helped to make those faraway fights come to life again with a graphic intensity that makes them, even to the new generation, rank with the most thrilling air stories of all time. For that one can forgive (but not forget) his errors of fact, and his terminological sideslips.—NORMAN MACMILLAN.

AIRCRAFT COMMUNICATION SYSTEMS. *J. H. H. Grover. Heywood, London, 1958. 127 pp. Illustrated. 22s. 6d.*

This book is a companion volume to "Radio Aids to Air Navigation" by the same author. It summarises the circuitry and operation of a number of specific radio equipments at present in common use for communication purposes in British civil aircraft.

It is divided into three parts: Part I covers the basic requirements for air/ground communication systems and goes on to describe the theoretical circuits of various British radio transmitters and receivers used in the medium and high frequency ranges of the radio spectrum. Part II deals with the operation of certain of the above equipments. Part III covers the circuits of some British equipments operating at very high frequency and also deals briefly with a few contemporary American transmitters and receivers, with an intercommunication equipment and with a selective calling equipment.

The weakest part of this book is the first chapter which attempts an all too cursory description of the relationship between frequency and modes of propagation and hence derives an explanation of the choice of frequency for the various operational requirements. There are several imprecise statements on the theory of propagation which could only mislead the uninitiated who would be well advised to derive their knowlege of this subject elsewhere. On the other hand, as the type of reader who is likely to be interested in the main body of the book, will be familiar with propagation theory, there seems little need for the inclusion of this matter.

The equipments covered in Part I are the following:—

In the A.D. series—87/8882, 97/108, 107A and B/114, 94, and in the STR series—18B/2 and 18C.

Part II gives operating procedures for 97/108, 107/114 and 18B/2 and 18C.

Part III provides theoretical description of AD115, STR12D, Collins 618S, Bendix TA-20A and RA18C, AD401 and Bendix SCL-3 (a selective calling system).

Although the information is quite comprehensive, it is condensed and should be regarded as supplementary to manufacturers' handbooks. Nevertheless, this will be a convenient reference book for students preparing for examination, and radio officers engaged in setting up equipment or fault finding.—A. C. MARCHANT.

LA PROPULSION PAR FUSÉES. *M. Barrère, A. Jaumotte, B. Fraeijs de Veubeke and J. Vandenkerckhove. Dunod, Paris, 1957. 389 pp. Illustrated. (In French).*

As is explained in an able preface by M. Maurice Roy (a contribution which makes the reviewer's task almost as superfluous as the necessity for cutting so many pages makes it laborious), this book is the outcome of a series of twelve sets of lectures given in Brussels early in 1956 under the aegis of Professor Jaumotte, each set of lectures forming a chapter of the present work. The first four chapters are contributed, either separately or in collaboration, by Jaumotte and Vandenkerckhove, covering the general basis of the subject, nozzle theory and solid rockets. Barrère wrote the next six chapters on liquid rockets, experimental technique and combustion instability, including one chapter on trajectories of unguided vehicles, while the last two chapters, on methods of guidance and optimum trajectories, are the work of Professor Fraeijs de Veubeke. Three of the authors are Belgian and the fourth, M. Barrère, French, so that the volume adds to its technical merits in being a good example of international co-operation.

Chapter 1 (Energy Properties of Rocket Propulsion) enumerates the broad types of rocket motor, with illustrated data on a number of past and present examples, and proceeds to define carefully the thrust, propulsive efficiency and other concepts required in later work.

Chapter 2 (Propulsive Nozzles and Characteristic Parameters of Rocket Motors) develops the familiar but very important one-dimensional gas dynamics of nozzles, presenting the salient results graphically, then proceeds to describe and illustrate the phenomena of over- and under-expansion, concluding with numerical calculations for the design of a rocket motor and its nozzle.

Chapter 3 (General Features of Solid Fuel Rockets) reviews the types of propellant grain employed, their burning characteristics and their dependence on temperature and pressure, types of propellant, methods of ignition, and the use of solid propellant exhaust products for pressurising liquid fuel tanks. Numerical examples are given on end-burning charges.

Chapter 4 (Solid Fuel Rockets of Arbitrary Burning Surface) extends this work to other configurations of charge, with emphasis on such practical topics as erosion and combustion instability.

Chapter 5 (General Study of Liquid Fuel Rockets) covers a multitude of topics: injector design, proportioning of combustion chambers, cooling, fuel systems, pump and turbine design.

Chapter 6 (Liquid Propellants) is concerned with the relevant physical and chemical properties of various propellants.

Chapter 7 (Experimental Technique in Rocket Propulsion) describes the desirable features of rocket test emplacements, the kinds of measurement required and means for detecting and recording them, and gives a number of examples of suitable test log sheets.

Chapter 8 (Combustion Instability in Liquid Fuel Rocket Motors: Low Frequency Instability) gives experimental examples of this form of instability and discusses the application of the Nyquist and Satche criteria to its analysis.

Chapter 9 (Study of High Frequency Instability) also presents interesting experimental records, and develops the technique of vibration analysis appropriate to this form of instability.

Chapter 10 (External Ballistics: Unguided Vehicles) develops the equations of motion of unguided rockets, discusses the influence of component weights, and gives numerical examples of single- and multi-stage units.

Chapter 11 (External Ballistics: Principles of Guidance, Transverse Accelerations) is misleadingly titled, in that it is concerned only with the various forms of pursuit trajectory (but not with beam riding) and the resulting accelerations as they affect missile design.

Chapter 12 (External Ballistics: Optimum Trajectories) applies the principles of the calculus of variations to the problem of minimising the propellant consumption between given end points.

All in all, this book represents a very able survey of the field of rocket propulsion, the theoretical contributions of the Belgian authors being well balanced by the practical information from the French contributor. Inevitably there are variations in style and emphasis, but it is hard to quarrel with the overall result. One could perhaps query whether the chapters on stability are rather too advanced to go well with the rest of the book, but at the same time they constitute its most original feature.—J. R. PALMER.

MAN AMONG THE STARS. *Wolfgang D. Miller. Harrap, London. 300 pp. Photos. 18s.*

SPUTNIKS INTO SPACE. *M. Vassiliev with Prof. V. V. Dobronravov. Souvenir Press, London. 147 pp. Photos. 15s.*

And still they come, the popular books on space-flight, very few adding anything in the way of information or ideas to those that came before them. One would be more surprised at their quantity, and perhaps even more critical of their quality, but for the knowledge that no less than 20,000 book titles on all subjects issue forth from British publishers alone, in any and every single year. Probably those dealing with astronautics are no worse than the majority of these.

The first of the above volumes is apparently of German origin, perhaps reaching the U.K. from across the Atlantic. With more of a philosophical bias than most of its contempories, it is not such a bad effort as many, but still far from being one of the best.

One approaches the second work with an inevitable lively interest, arising from *its* country of origin, which is the U.S.S.R., no less! Surely the comrades have something new to tell us? And of course they have—but not in this book.

First, the reader is somewhat put-off to discover that it is an English translation from an Italian translation from the Russian. This may explain some of the quaint phraseology, but can hardly excuse the many odd statements made in it, and still less such illustrations as the one of some sort of small tactical missile, captioned "A rare photograph . . . of a V.2." There are also a number of pictures showing what many people apparently still believe might have been the first-stage launching vehicle of the real sputniks—a huge twin-boom jet aircraft. Actually, these are stills from a recent Soviet cartoon film, having no more authenticity—in fact, a good deal less—than a similar production by Walt Disney. From a similar source comes an illustration of a row of "ginormous" rockets, opposite p. 109, which recently frightened the *Daily Express*.

One is at a loss to understand how Professor Dobronravov, of the Soviet Academy of Science, came to be mixed up in all this, especially since it originally appeared under the imprint of the State Publishing House, Moscow. One is left with the gloomy conclusion that perhaps the only field of achievement in which the Communists can do better than us decadent capitalists is the actual development of large rockets.—A. V. CLEAVER.

Additions to the Library

Aerodynamics of Supersonic Flight. *2nd Edition.* Alan Pope. Pitman, London. 1958. 243 pp. Illustrated. 35s. The review of the first edition (1950) in the JOURNAL, February 1952 (p. 139) ends "on the whole the book can be recommended to those requiring a broad and simply-minded introduction to the subject without complicated mathematics or a detailed description of the basic physical principles." This second edition is brought up-to-date to include the progress made in the subject since 1950; it now contains the complete aerodynamic theory and design of a simple supersonic wind tunnel and a brief discussion of supersonic performance from the practical side.

***Aeronautical Engineering Index 1956.** Institute of the Aeronautical Sciences, 1958. 236 pp. 10 dollars to members, 15 dollars to non-members. The Institute is struggling hard to catch up with the mass of material published each year. Nobody who needs to use aeronautical information (and the fringe subjects—and this contains some long fringes) can afford to be without this aeronautical "Enquire within upon everything." There are even 40 references to satellites.

CAA Story, The. U.S. Civil Aeronautics Administration, Washington. 1957. 17 pp. 11d.

Centrifugal Tendencies in Air Law. B. Cheng. Stevens, London. 1957. 28 pp. Reprinted from *Current Legal Problems 1957*, this is a brief study of some of the difficulties in the unification of rules of air law and their proneness, after unification, gradually to drift apart.

Complete Guide to London Airport. Sir Miles Thomas. Pitkin Pictorials, London. 1958. 32 pp. Illustrated. 2s. 6d. Revised since its first edition in 1956—the centre page now features the "Whispering Giant" instead of the "Monarch" Stratocruiser—this popular little book includes a spotters' guide with registrations of over 600 aircraft.

Examination of the Case for a London Heliport. Helicopter Association of G.B. 1958. 16 pp. 5s. A review of the "pros" for a London Heliport, with references to heliports and helicopter services in Europe and the United States. The requirements of, and possibilities for, the London area are discussed. Appendices contain historical notes, comparisons of journey times, availability of suitable helicopters, and notes on the proposed heliport at York Road, Battersea.

Fastest Man Alive, The. Frank K. Everest. Cassell, London. 1958. 204 pp. 21s. *To be reviewed.*

Introducing the Kolibrie. Netherlands Helicopter Industry N.V., Rotterdam. 1958. 20 pp. 5s.

Kerbspannungslehre (Theory of Notch Stresses). *2nd Edition.* Springer. 1958. 225 pp. Illustrated. 36 DM. (*In German.*) The first edition of this book appeared in 1937 and the English translation was published in 1946 by J. W. Edwards, Ann Arbor, Michigan. The new edition extends and enlarges the fundamental theory to meet current requirements in stress calculations and includes a new theory which takes into account non-linear deformation.

Mathematical Theory of Compressible Flow. R. Von Mises. Completed by H. Geiringer and G. S. S. Ludford. Academic Press, New York. 1958. 514 pp. 15 dollars. *To be reviewed.*

Natural Aerodynamics. R. S. Scorer. Pergamon, London. 1958. 312 pp. 60s. *To be reviewed.*

No Echo in the Sky. Harald Penrose. Cassell, London. 1958. 134 pp. 15s. *To be reviewed.*

On the Analysis of Non-Linear Viscoelastic Structures with Temperature Gradients. H. H. Bleich. 1958. 29 pp. **Non-Linear Creep Deformations of Columns of Rectangular Cross Section.** H. H. Bleich and O. W. Dillon. 1958. 33 pp. **Dominance of Shear Stresses in Early Stages of Impulsive Motion of Beams.** H. H. Bleich and R. Shaw. 1958. 21 pp. Three reports from the Department of Civil Engineering and Engineering Mechanics of Columbia University, New York.

Polar Atmosphere Symposium: Agardograph 29. Part II. Ionospheric Section. K. Weekes (*Editor*). Pergamon, London. 1957. 213 pp. 60s. *To be reviewed.*

Proceedings of the National Conference on Aeronautical Electronics, 1957. U.S. Institute of Radio Engineers, Publications Committee of Nat. Conf. Aero. El., Ohio. 409 pp. Illustrated. 40s. A photo-copied volume containing over 80 papers read at the Conference, but without discussions. The papers are grouped under the general headings of equipment applications, component parts, navigation, communications, electronic equipment, management (including research) environment and air safety.

Proceedings of the Society for Experimental Stress Analysis, Vol. XV, No. 2. C. V. Mahlmann and W. M. Murray (*Editors*). Society for Experimental Stress Analysis, Cambridge, Mass. 1958. 147 pp. Illustrated. This second half of Volume XV contains papers on thermal stresses, photoelasticity, strain gauges, dynamic tests of propeller blades, a machine for high temperature fatigue testing and residual stresses in cylinders. Also included is a cumulative index (with author and subject classification) of the 546 papers published in the fifteen volumes of the series.

Reason and Chance in Scientific Discovery. R. Taton. Hutchinson, London. 1957. 171 pp. Illustrated. 30s. Using practical examples drawn from the lives and works of distinguished scientists the author examines the relative roles of active purpose and chance in the processes of scientific discovery and gives "a penetrating insight into the workings of the inventive mind."

Right to Fly, The. B. Cheng. Reprinted from Grotius Society Transactions for 1956. Stevens, London. 1956. 30 pp. The author is Lecturer in International Law and Air Law at University College, London.

Selected Bibliography—Fatigue, Stress, Bodily Change and Behavior. W. Bevan and R. M. Patton. Wright Air Development Center, Ohio. 1957. 63 pp. 16s. A bibliography of 883 references, covering the period 1946-1956, and relevant to an experimental investigation of air crew fatigue associated with relatively long confinement within the flight station of an advanced design aeroplane.

Tables of Temperature, Relative Humidity and Precipitation for the World. Parts I, IV, V, VI. Meteorological Office. H.M.S.O., London. 1958. 8s., 20s., 12s. and 5s. 6d. respectively. Tables for a carefully chosen and representative selection of places, in book form. The regions covered by the various Parts are:—Part I. North America, Greenland and the North Pacific Ocean. Part II. Central and South America, the West Indies and Bermuda. Part III. Europe and the Atlantic Ocean North of 35°N. Part IV. Africa, the Atlantic Ocean South of 35°N. and the Indian Ocean. Part V. Asia. Part VI. Australasia and the Southern Pacific Ocean, including the corresponding sectors of Antarctica. Parts II and III not yet available.

Transient Response from Frequency Response. V. V. Solodovnikov *et al.* Infosearch, London. 1958. 193 pp. Illustrated. 42s. A Varityped volume, translated from the Russian giving the procedure for obtaining transient response from frequency response; the procedure consists in the graphic approximation of the closed-loop frequency response by line segments and adding up the transients corresponding to the resultant trapezoids. In three parts: theory of the method, illustrative examples, and tables of functions.

Vistas in Astronautics. M. Alperin *et al.* (*Editors*). Pergamon, New York. 1958. 330 pp. 105s. *To be reviewed.*

* *Reference only.*

Reports

AERODYNAMICS

Boundary Layer—*see also* Thermo-Aerodynamics

Skin-friction measurements in incompressible flow. D. W. Smith and J. H. Walker. N.A.C.A. T.N. 4231. *March* 1958.
Experiments have been conducted to measure the local surface-shear stress and the average skin-friction coefficient in incompressible flow for a turbulent boundary layer on a smooth flat plate having zero pressure gradient. Data were obtained for a range of Reynolds numbers from one million to 45 million.—(1.1.3.1).

Turbulent shearing stress in the boundary layer of yawed flat plates. H. Ashkenas. N.A.C.A. T.N. 4140. *April* 1958.
Hot-wire anemometer measurements of the turbulent shearing stress in a turbulent boundary layer on a yawed flat plate are presented. Two plates with angles of yaw of 0° and 45° were studied. Measurements of the intensity of turbulence were made simultaneously with the shear measurements, using a technique developed by the author. The experimental procedure is reviewed and an attempt is made to evaluate the precision of the results.—(1.1.3.1).

Analysis of turbulent flow and heat transfer on a flat plate at high Mach numbers with variable fluid properties. R. G. Deissler and A. L. Loeffler. N.A.C.A. T.N. 4262. *April* 1958.
A previous analysis of turbulent heat transfer and flow with variable fluid properties in smooth passages is extended to flow over a flat plate at high Mach numbers, and the results are compared with experimental data. Velocity and temperature distributions are calculated for a boundary layer with appreciable effects of frictional heating and external heat transfer. Viscosity and thermal conductivity are assumed to vary as a power of the temperature, Prandtl number and specific heat are taken as constant. Skin friction and heat transfer coefficients are calculated and compared with incompressible values. The rate of boundary layer growth is obtained for various Mach numbers.—(1.1.3.4 × 1.9.1).

Compressible Flow—*see also* Wings and Aerofoils

Extreme speeds and thermodynamic states in supersonic flight. K. Oswatitsch. N.A.C.A. T.M. 1434. *April* 1958.
Typical of all cases of high-speed flow is the conversion of high kinetic energy into extreme thermodynamic states with temperatures of several thousand degrees; frequently, the gas is dissociated and ionised. A small sensitivity to high speeds is characteristic of gases of low molecular weight. With a minimum of mathematical and physical complexity, these matters are discussed in relation to meteors, shock tubes, ram-jets, and rockets. The discussion is directed primarily to experts in neighbouring fields and interested novices.—(1.2.3 × 27 × 30).

The interaction of a reflected shock wave with the boundary layer in a shock tube. H. Mark. N.A.C.A. T.M. 1418. *March* 1958.
By theoretical analysis the existence of several different types of interaction in different ranges of initial shock Mach number in predicted. This analysis is verified experimentally. The most complicated interaction is studied in detail, and a model is proposed. The features of the phenomenon are analysed, based on this model, and are checked experimentally. The case of interaction with a turbulent boundary layer is also considered. A method is proposed whereby the effect of the laminar boundary layer interaction on the strength of the reflected shock may be calculated, and a comparison with experimental results is presented.—(1.2.3.2 × 1.5.1.4).

Prandtl-Meyer expansion of chemically reacting gases in local chemical and thermodynamic equilibrium. S. P. Heims. N.A.C.A. T.N. 4230. *March* 1958.
It is shown how Prandtl-Meyer flow, in which chemical reactions are occurring and are in equilibrium, can be simply and exactly calculated. The property of air which governs the flow is found to depend only on the ratio of enthalpy to the square of the speed of sound; the analogous quantity for an inert gas depends only on the ratio of specific heats. A numerical example is given.—(1.2.3.1 × 1.9).

Experimental study of the equivalence of transonic flow about slender cone-cylinders of circular and elliptic cross section. W. A. Page. N.A.C.A. T.N. 4233. *April* 1958.
An experimental investigation at transonic speeds of the pressures on a flat, winglike, elliptic cone cylinder and its equivalent body, a circular cone cylinder, provides confirming evidence of the equivalence relationships theoretically predicted by transonic slender-body theory.—(1.2.2 × 1.6.1).

A second-order shock-expansion method applicable to bodies of revolution near zero lift. C. A. Syvertson and D. H. Dennis. N.A.C.A. Report 1328. 1957. *Supersedes N.A.C.A. T.N.* 3527.
A second-order shock-expansion method applicable to bodies of revolution is developed by the use of the predictions of the generalised shock-expansion method in combination with characteristics theory. Equations defining the zero-lift pressure distributions and the normal force and pitching moment derivatives are derived.—(1.2.3.1).

Minimum wave drag for arbitrary arrangements of wings and bodies. R. T. Jones. N.A.C.A. Report 1335. 1957. *Supersedes T.N.* 3530.
Studies of various arrangements of wings and bodies designed to provide favourable wave interference at supersonic speeds lead to the problem of determining the minimum possible value of the wave resistance obtainable by any disposition of the elements of an aircraft within given dimensions defined by a region. Under the assumptions that the total lift and the total volume of the aircraft are given, conditions that must be satisfied if the drag is to be a minimum are found.—(1.2.3.1).

Control Surfaces—*see also* Wings and Aerofoils

Mesure de coefficients de moment de charnière d'aileron sur une aile droite de faible allongement. S. Chopin et H. Loiseau. O.N.E.R.A. NT. 46. 1958. (*In French.*)
The experiments on a rectangular wing were made as part of a wind tunnel programme for studying flutter with two degrees of freedom (flexural-aileron rotation).—(1.3.1 × 1.10.2.2).

Internal Flow—*see* Compressible Flow

Loads—*see* Compressible Flow
Wings and Aerofoils

Stability and Control—*see also* Wings and Aerofoils
Aeroelasticity

Experimental and predicted longitudinal and lateral-directional response characteristics of a large flexible 35° *swept-wing airplane at an altitude of* 35,000 *ft. H. A. Cole et al. N.A.C.A. Report* 1330. *Supersedes N.A.C.A. T.N.* 3874.
Longitudinal and lateral-directional response to control surface motions are presented for a large flexible swept-wing aeroplane over a range of Mach numbers at 35,000 ft. Frequency responses, transfer functions, and stability derivatives are evaluated from transient response to elevator, aileron, and rudder inputs. Comparisons are made between response characteristics predicted for the rigid and flexible aeroplane, and those evaluated from transient flight data.—(1.8 × 2).

A theoretical analysis of the effect of engine angular momentum on longitudinal and directional stability in steady rolling maneuvers. O. B. Gates and C. H. Woodling. N.A.C.A. T.N. 4249. *April* 1958.—(1.8.1.1 × 1.8.2.1).

Thermo-Aerodynamics—*see also* Boundary Layer
Compressible Flow

Stagnation-point heat transfer to blunt shapes in hypersonic flight, including effects of yaw. A. J. Eggers et al. N.A.C.A. T.N. 4229. *April* 1958.
An approximate theory is developed for the heat flux to the stagnation region of blunt bodies in hypersonic flight.—(1.9.1).

Effects of Mach number and wall-temperature ratio on turbulent heat transfer at Mach numbers from 3 to 5. T. Tendeland. N.A.C.A. T.N. 4236. April 1958.
Heat-transfer data were evaluated from temperature time histories measured on a cooled cone-cylinder model with turbulent flow at Mach numbers of 3·00, 3·44, 4·08, 4·56, and 5·04. The effects of Mach number and wall-temperature ratio on Stanton number are compared with predictions from existing theories—(1.9.1 × 1.1.3.4).

WINGS AND AEROFOILS—*see also* CONTROL SURFACES
AEROELASTICITY

Calculation of derivatives for a cropped delta wing with an oscillating constant-chord flap in a supersonic air stream. J. Watson. R. and M. No. 3059. 1958.
The lift, pitching moment and hinge moment are derived for a delta wing with a trailing-edge flap of constant chord when the wing is at zero incidence in a supersonic air stream and the flap oscillates harmonically with small amplitude and low frequency. It is assumed that the wing is sufficiently thin and the amplitude of oscillation sufficiently small to permit the use of linearised theory. Expressions for the various control derivative coefficients are obtained for a particular delta wing of aspect ratio 1·8 and taper ratio 1/7. The investigation covers partial-span flaps; in each case there is a lower limit to the Mach numbers for which the theory applies, though from practical considerations this restriction is not serious. The derivatives are evaluated and tabulated for Mach numbers of 1·1, 1·2, 1·4, 1·6, 2·0.—(1.10.1.2 × 1.8.2.2).

Calculation of derivatives for a cropped delta wing with subsonic leading edges oscillating in a supersonic air stream. J. Watson. R. and M. No. 3060.
The lift, pitching moment and full-span constant-chord control hinge-moment are derived for a cropped delta wing describing harmonic plunging and pitching oscillations of small amplitude and low-frequency parameter in a supersonic air stream. It is assumed that (*a*) the wing has subsonic leading edges, (*b*) the wing is sufficiently thin and the Mach number sufficiently supersonic to permit the use of linearised theory. Expressions for the various derivative coefficients are obtained for a particular delta wing of aspect ratio 1·8 and taper ratio 1/7; these are evaluated and tabulated for Mach numbers of 1·1, 1·15, 1·2, 1·3, 1·4, 1·5, 1·6 and 1·944.—(1.10.1.2 × 1.8.2.2).

The wave drag of non-lifting combinations of thin wings and "non-slender" bodies. L. M. Sheppard. R. and M. No. 3076.
The methods of wave-drag estimation known as the area rule and transfer rule are restricted to non-lifting combinations of thin wings and slender bodies. The application of the multiple method to fuselage design for low combination wave drag is discussed with special reference to an elliptic wing-body combination.—(1.10.1.2 × 1.2.3.1).

Lift and center of pressure of wing-body-tail combinations at subsonic, transonic, and supersonic speeds. W. C. Pitts et al. N.A.C.A. Report 1307. 1957.
A method is presented for calculating the lift and centres of pressure of wing-body and wing-body-tail combinations at subsonic, transonic, and supersonic speeds. A set of design charts and a computing table are presented which reduce the computations to routine operations.—(1.10.1.2 × 1.2 × 1.3).

Theoretical and experimental investigation of the subsonic-flow fields beneath swept and unswept wings with tables of vortex-induced velocities. W. J. Alford. N.A.C.A. Report 1327. 1957. Supersedes T.N. 3738.
The flow characteristics around swept and unswept wings necessary in first-order estimations of aerodynamic loadings, trajectories, and jettison characteristics of missiles, fuel tanks, or bombs as determined experimentally are compared with the flow fields as calculated by potential-flow theory.—(1.10.1.2 × 1.6.1).

A method for the calculation of wave drag on supersonic-edged wings and biplanes. H. Lomax and L. Sluder. N.A.C.A. TN. 4232. March 1958.
A method is presented for finding the lift, moment, and drag on three-dimensional wings or biplanes with supersonic edges and a straight trailing edge normal to the free stream. The minimum wave drag for fixed lift or volume is given for several special cases.—(1.10.1.2).

HELICOPTER AERODYNAMICS—*see* PROPELLERS

TESTING AND INSTRUMENTS

An investigation of the frequency response of Pitot probes and preliminary measurements of the Pitot pressure fluctuations in the N.A.E. 5 in. pilot supersonic wind tunnel. R. Westley. N.A.E. Report LR-214. December 1957.
The frequency response characteristics of Pitot probes were investigated with a view to the use of probes for the measurement of the Pitot head fluctuations in a high speed wind tunnel. A sound source method was used to calibrate the responses of four Pitot probes and a hypodermic boundary layer probe.—(1.12.5).

Hypersonic facilities in the aerodynamics department Royal Aircraft Establishment. P. A. Hufton. AGARD Report 146. July 1957.
A description is given of the hypersonic facilities at the Royal Aircraft Establishment, and the various problems leading to their development are discussed. Four Appendices are included: (1) A note on multiple diaphragm shock tubes; (2) A note on combustion driven shock tubes; (3) Some methods of evaluating imperfect gas effects in aerodynamic problems; (4) Development of the R.A.E. 6 in. diameter shock tube.—(1.12.1.3).

AEROELASTICITY

See also AERODYNAMICS—STABILITY AND CONTROL

Tables of aerodynamic flutter derivatives for thin wings and control surfaces in two dimensional supersonic flow. I. T. Minhinnick and D. L. Woodcock. C.P. 382. 1958.
Tables of the two-dimensional supersonic flutter derivatives for infinitesimally thin aerofoils are given. Only the derivatives giving the forces on wings and control surfaces due to wing motion are tabulated but it is shown how the remaining derivatives can be very easily obtained from those tabulated.—(2).

The effect of wing torsion on aileron-tab flutter. H. Hall. R. and M. No. 3072. 1958.
The results of an investigation into the effects of wing torsion in a ternary-type spring-tab flutter are given. The results are for a series of calculations on an idealised system having degrees of freedom in wing pitch, rotation of the control surface and rotation of the tab; the pitching degree of freedom is spring restrained and is intended to represent wing torsion. The tab is restrained as a trim tab or pure aerodynamic servo tab, but the results are expected to apply qualitatively to a spring tab.—(2).

A comparison of the measured and predicted flutter characteristics of a series of delta wings of different aspect ratios. H. Hall and E. W. Chapple. R. and M. No. 3071. 1958.
The results of tests to investigate the aerodynamic effects of aspect ratio on the flutter of delta wings that are virtually rigid but are flexibly supported at the root are given. A function representing the aerodynamic effects of aspect ratio on wing flutter speeds is derived from the experiments. Flutter calculations are made using this function as a correction to the derivatives obtained from two-dimensional theory. Calculations are made using derivatives obtained from three-dimensional theory.—(2).

On the integral equations of two-dimensional subsonic flutter derivative theory. D. E. Williams. R. and M. No. 3057. 1958.
The result of an attempt to find an analytical solution of Possio's integral equation is given—the equation which connects the downwash and the pressure distribution on an aerofoil oscillating in two-dimensional subsonic compressible flow. A method is given for solving this problem and for solving the corresponding problem in incompressible flow (the solution of Birnbaum's integral equation).—(2).

Oscillating wings in compressible subsonic flow. W. P. Jones. R. and M. 2855. 1957.
The problem of estimating flutter and stability derivatives for wings of finite span describing simple harmonic oscillations in compressible flow is considered. It is shown that the problem can be reduced to a similar one for an equivalent wing in incompressible flow. The mode of oscillation is different but related to that of the original wing and leads to a more complicated condition for tangential flow.—(2 × 1.8.2.2).

Comparison of several methods for obtaining the time response of linear systems to either a unit impulse or arbitrary input from frequency-response data. J. J. Donegan and C. R. Huss. N.A.C.A. Report 1324. 1957. *Supersedes N.A.C.A. T.N.* 3701.
The comparison indicates that all of the methods give good accuracy when applied to a second-order system; the main difference is the required computing time to obtain the same degree of accuracy. When applied to higher order systems, however, the methods generally classified as inverse Laplace transform methods were found most effective. Some discussion is given of the use of the methods as flight-data-analysis techniques in predicting loads and motions for a flexible aircraft when the aircraft frequency response is known.—(2).

Application d'une méthode de détermination expérimentale des forces aérodynamiques instationnaires relatives a une aile rigide oscillant en soufflerie. R. Dat et M. Trubert. O.N.E.R.A. NT. 44. 1958. (*In French.*)
It is possible to determine in a wind tunnel the unsteady aerodynamic forces on a model in relation to a particular degree of freedom by oscillating the model in this degree and determining its natural frequency and damping for a range of wind speeds. A relatively simple method is derived which does not use phase measurements. This method has been applied to a wing section in a small wind tunnel and flutter experiments in two degrees of freedom have verified the results. The small size of the working sections means that the aerodynamic coefficients found in the tunnel should be treated with reserve when applied to a free air case.—(2 × 1.10.2.1).

Aeroelastisches Kolloquium in Göttingen am 16. *und* 17. *April* 1957. *Max-Planck-Institut. Mitt. Nr.* 18. 1958. (*In German.*)
Papers given at a symposium on aeroelasticity held in Göttingen are given. The authors include H. G. Kussner, A. I. van de Vooren, G. de Vries, E. Gruschwitz, H. Bergh, H. Merbt and S. Hansson, and J. Schoen.—(2).

DESIGN AND CONSTRUCTION

Correlation, evaluation, and extension of linearized theories for tire motion and wheel shimmy. R. F. Smiley. N.A.C.A. Report 1299. (*Supersedes T.N.* 3632.) 1957.
An evaluation is made of the existing theories of linearised tyre motion and wheel shimmy. It is demonstrated that most of the previously published theories represent varying degrees of approximation to a summary theory developed herein which is a minor modification of the basic theory of Von Schlippe and Dietrich.—(4.2.2.3).

AIRCRAFT OPERATION

Flight investigation of some airworthiness problems of civil boat seaplanes. J. Taylor et al. R. and M. No. 3017. 1958.
A general investigation has been made into measurement, control and performance problems associated with boat seaplane take-off and initial climb. Particular attention was paid to engine failure during take-off and initial climb, and also to the criteria to be used for defining the minimum speed for control in the air. The aircraft employed was a Solent flying-boat of weight 78,000 lb., powered by four Hercules Mark XIX engines.—(5 × 13).

Determination of daytime conspicuity of transport aircraft. W. D. Howell. C.A.A. T.D.R. No. 304. *May* 1957.
The conspicuity of present-day transport aircraft was determined by measuring in daytime flight the distances at which pilots of one aircraft became aware of another DC-3 aircraft, normally painted and equipped, as it approached from various angles on courses which would result in collisions. Also during these collision runs, the threshold distance, ultimate distance from which a DC-3 aircraft can be seen with the naked eye, was recorded.—(5.3).

Simulation tests for army air traffic control. T. K. Vickers. C.A.A. T.D.R. No. 298. *May* 1957.
The testing of a number of concepts which have been proposed to meet the specialised requirements of Army aviation during the next few years are described. These concepts cover such subjects as airway structures, airport designs, and navigation and scheduling procedures, to define a simplified system for the control of large numbers of logistic and support aircraft in almost complete radio silence.—(5).

Ground reflection of jet noise. W. L. Howes. N.A.C.A. T.N. 4260. *April* 1958.
The effect of a reflecting plane is determined from theory and experiment. From the theoretical characteristics of far-field acoustic decay a correction to free-field procedure is developed for data obtained in the presence of a plane.—(5 × 32.2.3).

ELECTRONICS

P.P.I. presentation of time-shared videos having synchronized or unsynchronized antenna rotation rates. W. E. Miller and L.B.Ii. C.A.A. T.D.R. No. 290. *June* 1957.
A Navy Type SPA-8A radar plan-position indicator was modified to display two synchronised radar-video inputs on a time-shared basis. A characteristic of these radar inputs was that they possessed common or synchronised triggers and either synchronised antenna rotation with fixed azimuth displacement or unsynchronised antenna rotation. Two applications for this type of indicator and the modification and factors to be considered when time-sharing are outlined.—(11).

Improvement of echo suppression in D.M.E. transponders. A. W. Randall et al. C.A.A. T.D.R. No. 309. *June* 1957.
Experience gained through the use of ground and airborne distance-measuring equipment has indicated that air/ground path echo signals can be responsible for occasional loss or erratic indication of distance information. This report describes the manner in which interrogation-path echo signals affect the performance of the transponder, and it indicates modifications which may be made to D.M.E. transponders to eliminate the ill effects of echo signals.—(11).

VHF omnirange reflections from a single tree. R. B. Flint and A. E. Frederick. C.A.A. T.D.R. No. 314. *June* 1957.
The performance of a very-high-frequency omnirange located at various distances from a single tree is described. Tests were also conducted with the horizontal limbs of the tree removed.—(11).

FLIGHT TESTING

See AIRCRAFT OPERATION

HYDRODYNAMICS

Résolution de problèmes d'infiltrations a surface libre au moyen d'analogies électriques. P. H. de la Marre. Pubs. Sc. et Tech. No. 340. 1958. (*In French.*)
A choice of methods is given for solving experimentally, by means of electrical analogies, practical filtration problems. Four classes of problem are detailed; plane steady flows in homogeneous isotropic media (solved by using models made of conducting paper); plane steady flows in heterogeneous, anisotropic media (using a grid of conductances); three-dimensional problems (using conducting plaster or grids); non-steady flows. Theory of grids of conductances, with unequal spacings and any boundaries is given.—(17.1 × 18.1).

INSTRUMENTS AND EQUIPMENT

See also HYDRODYNAMICS

Central automatic data processing system. By the Staff of the Lewis Laboratory. N.A.C.A. T.N. 4212. *April* 1958.
A centralised system has been developed and installed for the automatic recording and processing of data from several remotely located testing stations. Pressures, voltages, frequencies, and other pertinent variables are recorded on magnetic tape in digital form. The magnetic tape is fed into a high-speed digital computer to convert raw data to dimensioned quantities and to compute any terminal calculations called for by the test engineer. Computed data can be returned to the test engineer the next day; raw data can be returned immediately. The system has been in operation for two years.—(18).

Travaux francais relatifs à la réalisation et l'étude de ferrures de grandes dimensions en alliages de titane. E. Gammal. AGARD Report 97. *April* 1957. (*In French.*)
The results of strength tests carried out on forgings of titanium alloy are given.—(21.2.2).

Regularities in creep and hot-fatigue data. Part I. A. Graham and K. F. A. Walles. C.P. 379. 1958.
Published experimental results are assembled to support a previous theory of uniaxial deformation, and the theory is used to analyse published data on the creep-rupture and hot-fatigue of engineering materials. The theory enables data for different times and temperatures to be classed together, thereby providing information over a much greater range of time than could practicably be covered by experiments at a single temperature.—(21.2 × 31.2.2.1).

MATERIALS

Regularities in creep and hot-fatigue data. Part II. K. F. A. Walles and A. Graham. C.P. 380. 1958.
This report continues the comparison with experimental data of the theory of Part I (C.P. 379). Data for creep-rupture, creep rate and hot-fatigue are considered.—(21.2 × 31.2.2.1).

Measurements of total hemispherical emissivity of various oxidized metals at high temperature. W. R. Wade. N.A.C.A. T.N. 4206. *March* 1958.
The results of measurements of total hemispherical emissivity over the temperature range of 600° to 2,000°F for various heavily oxidized metals are presented, together with a description of the equipment and the procedures used.—(21.2).

Effect of overheating on creep-rupture properties of M-252 alloy. J. P. Rowe and J. W. Freeman. N.A.C.A. T.N. 4224. *March* 1958.
The effects of overheats were evaluated in terms of the changes in creep-rupture properties at 1,500°F of M-525 alloy under stresses within the range of rupture strengths of the alloy for 80 to 1,000 hours. The results are compared with results of similar tests on S-816 and HS-31 alloys.—(21.2.2).

Inorganic transparencies for aircraft enclosures. C. H. Hahner and M. J. Kerper. AGARD Report 161. *November* 1957.
Work being done under the sponsorship of the Wright Air Development Center to obtain additional information on a few selected glasses that are believed to be most suitable for use in aircraft is described. The glasses selected for study are ones that can be made in the form of polished plate glass of the required sizes.—(21.3.3).

MATHEMATICS

Fonctions thêtaelliptiques et dzêtaelliptiques. Application au calcul de l'écoulement autour de l'aile conique. R. Legendre. O.N.E.R.A. Pub. No. 91. 1958. (*In French.*)
Definitions and studies of the properties of elliptic functions and integrals are performed without using the intermediate Jacobian or Weierstrassian functions in order that the calculations may be modelled on those which are applied to rational integrals. The advantages are illustrated by an application to the solution of a problem in mechanics of fluids.—(22.1).

MECHANICAL ENGINEERING

Relation of journal bearing performance to minimum oil-film thickness. F. W. Ocvirk and G. B. DuBois. N.A.C.A. T.N. 4223. *April* 1958.
The minimum thickness of the oil film is used as a basic variable in performance curves of plain journal bearings under a steady load. Analytical curves based on the short-bearing approximation and the solution of Cameron and Wood are compared with various experimental data. Load capacity and predicted film thickness at friction-curve hook points are correlated with peak-to-valley surface roughnesses. Analytical curves show the effect of bearing-clearance changes on friction power loss, film thickness, and peak pressure in the oil film.—(23.1).

METEOROLOGY

The sampling errors of atmospheric turbulence measurements. N. I. Bullen. R. and M. No. 3063. 1958.
Estimates of atmospheric turbulence from counting accelerometer records show a large scatter. The simple assumption of a random distribution of gusts is inconsistent with this scatter. A formula which takes account of the variations in gust density is given.—(24).

Cloud-droplet ingestion in engine inlets with inlet velocity ratios of 1·0 *and* 0·7. *R. J. Brun. N.A.C.A. Report* 1317. 1957.
The paths of cloud droplets into two engine inlets are calculated. The amount of water in droplet form ingested by the inlets and the amount and distribution of water impinging on the inlet walls are obtained from these droplet-trajectory calculations.—(24).

A flight evaluation and analysis of the effect of icing conditions on the ZPG-2 airship. W. Lewis and P. J. Perkins. N.A.C.A. T.N. 4220. *April* 1958.
Test flights conducted by the U.S. Navy in a number of typical icing conditions are described. The airship operated successfully in all icing conditions encountered, but the desirability of limited protection for certain components was indicated.—(24).

POWER PLANTS

See also AERODYNAMICS—COMPRESSIBLE FLOW

Drop-size distributions for impinging-jet breakup in airstreams simulating the velocity conditions in rocket combustors. R. D. Ingebo. N.A.C.A. T.N. 4222. *March* 1958.
Data obtained with a high-speed camera were analysed using the Nukiyama-Tanasawa expression. A range of orifice diameters, liquid-jet velocities and velocity differences between the airstream and the liquid jets gave maximum-observed drop diameters ranging from 180 to 1,160 microns.—(27.3).

PRODUCTION ENGINEERING

Les normes francaises et internationales sur le controle de la qualité. A. Pallez. AGARD Report 152. *November* 1957. (*In French.*)—(28).

PROPELLERS

Experimental investigation of the drag of flat plates and cylinders in the slipstream of a hovering rotor. J. W. McKee and R. L. Naeseth. N.A.C.A. T.N. 4239. *April* 1958.
An experimental study has been made of the drag of flat plates and cylinders in the slipstream of a rotor for the condition of hovering away from the effect of the ground. An attempt to compare model drag coefficients with values obtained from wind-tunnel tests led to rather inconclusive results, particularly for the cylinders.—(29.1 × 1.11.1).

REFERENCE LITERATURE

See AERODYNAMICS—COMPRESSIBLE FLOW

FATIGUE

See MATERIALS

SCIENCE-GENERAL

See also AIRCRAFT OPERATION

Effect of jet temperature on jet-noise generation. V. G. Rollin. N.A.C.A. T.N. 4217. *March* 1958.
Sound measurements were made on a $\frac{5}{8}$ in. model air jet over a range of pressure ratios from 1·3 to 1·9 and jet air temperatures from 80° to 1,000°F.—(32.2.3).

STRUCTURES

LOADS

The aircraft structural factor of safety. G. N. Mangurian. AGARD Report 154. *November* 1957.
The case for a review of the Aircraft Structural Factor of Safety is presented in the light of appreciable advancements in structural and aerodynamic knowledge. In certain design aspects, a reduction in the presently required ultimate factor of safety is realistic and should be considered; in other aspects, a reduction should not be considered at present.—(33.1.3).

Reflexions generales sur la sécurité des materiaux et des structures. E. M. Prot. AGARD Report 151. *November* 1957. (*In French.*)—(33.1.3).

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